DEGREE PROGRAMME IN WIRELESS COMMUNICATIONS ENGINEERING

MASTER'S THESIS

POWERING REMOTE AREA BASE STATIONS BY RENEWABLE ENERGY

Author	ALI RAZA TAHIR
Supervisor	Dr. HARRI SAARNISAARI
Second Examiner	Dr. HARRI POSTI

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ABSTRACT

The number of cellular subscriptions have seen a tremendous growth in the last decade and to provide connectivity for everyone has led to growth in number of base stations (BSs). BSs installed at places where reliable grid power is not available has increased and will continue to increase in the coming years to connect everybody on the globe. Energy and cost efficiency is becoming a criterion of ever increasing importance in the information and communication technology sector. Energy and cost efficiency is especially important for remote areas where providing mobile communication services is inhibited by the economic drawback of low revenue potential.

In this thesis, we discuss the role of BS power consumption in the cellular networks in order to investigate approaches to lower the overall power consumption of the cellular network. The thesis covers structure of a BS and the power consumption of its components. Previous works and research approaches proposed to reduce the power consumption of BSs and to what extent they can lower the power requirement are discussed. Reducing the BS power consumption will reduce the operating cost for the networks and ease the deployment of BSs in remote areas. Also discussed are the two key technical features of 5th generation cellular access networks (beam forming through massive multiple input multiple output antenna systems and ultra-lean system design) that are promising in terms of reducing the BS power consumption.

Furthermore, we discuss viable sources of renewable energy that can be used to power BSs in the remote areas. An overview of the renewable energy resources that can be used for this purpose (solar and wind energy) and their availability in different regions is discussed. The setups for harnessing solar and wind energy to generate power are presented in this thesis.

For different cases requirements of wind and solar energy systems to power the BSs are calculated. Results show that while solar energy alone is a feasible option in regions at low latitude, small solar energy systems of 4-7 kW rated output power can easily power BS during the entire year. But in regions of high latitude using solar energy alone cannot meet the BS power requirement as there are long durations of very low or negligible solar irradiation levels. Furthermore, the energy produced by small wind energy setups at different wind speeds is investigated for the purpose of powering BSs. We discuss the range of windspeed levels for which the energy produced is sufficient to power a BS. Areas with average windspeeds of 5-8 m/s are very suitable for using wind energy as a source of power for BSs. Hybrid energy systems to power BSs and also a few energy storage options to store excess power are also discussed in this thesis.

Key words: Mobile base station, Off grid base stations, Renewable energy, Grid Power, Solar energy, Wind energy, Hybrid energy systems.

Table of contents

FOREWORD

I would like to thank the Center for wireless communications (CWC) in University of Oulu for receiving me as a master student, and for this valuable opportunity providing me access to laboratory facilities and all other kinds of support throughout my thesis project.

In particular, I would like to express my sincere gratitude to Dr. Harri Saarnisaari, my thesis examiner at Center for wireless communications (CWC), for his support, inspiration, and patience in guiding me through the whole process. Even though you have had a very busy schedule to keep up with you have always helped me through technical difficulties and you always answered my questions with great patience and helped me stay on the right track. I have gained tremendous learning and valuable skills from you while working on my thesis which I would keep with me for my whole career.

I would like to give special thanks to my mother and father who urged me to do masters and supported me throughout this entire process. With your love and prayers have I been able to come this far, and I cannot thank you enough for all you have done for me.

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Ali Raza Tahir

LIST OF ABBREVIATIONS AND SYMBOLS

AC	alternating current
A/C	air conditioner
AI	antenna interface
A/D	analog to digital
APAC	Asia and Pacific
BB	baseband
BS	base station
Capex	capital investment
DC	direct current
DG	diesel generator
DOD	depth of discharge
DPD	digital pre-distortion
DTX	discontinuous transmission
EIRP	effective isotropic radiated power
ET	envelope tracking
GaN	gallium nitrate
GHG	greenhouse gasses
ICT	information and communications technology
Li-ion	lithium ion
LTE	long term evolution
MENA	Middle East and North Africa
MIMO	multiple input multiple output
NiFe	nickel ferrous
NiMH	nickel metal hydride
Opex	operating cost
PV	photo voltaic
PA	power amplifier
RF	radio frequency
RRH	remote radio head
SOC	state of charge
TRx	transmitter
UE	user equipment
3GPP	third generation partnership project
5G	fifth generation

σ	loss factor
η	efficiency
δ	DTX capacity
Δ_p	load dependant power consumption

φ	elevation half power beamwidth angle
θ	azimuth half power beamwidth angle
A_{batt}	battery bank autonomy
F_{pv}	PV derating factor
$L_{prim-avg}$	average daily load
Q_{pv}	output PV energy
Q_{nom}	capacity of a battery
Q_{life}	lifetime throughput of battery
Q_{thr}	annual battery throughput
R_{batt}	battery lifecycle
$R_{batt,f}$	battery float life
V_{nom}	voltage of a battery
Y_{pv}	PV capacity

1 INTRODUCTION

The telecommunication sector has a very significant role in the global economy and the way people share information amongst each other. At the end of the year 2016, there are around 7.377 billion mobile cellular subscriptions across the world compared to the 2.205 billion mobile cellular subscriptions in the year 2005. Although the number of subscribers and subscriptions differ greatly [1]. Figure 1.1 shows the increase in mobile phone subscriptions over the course of past decade [2].

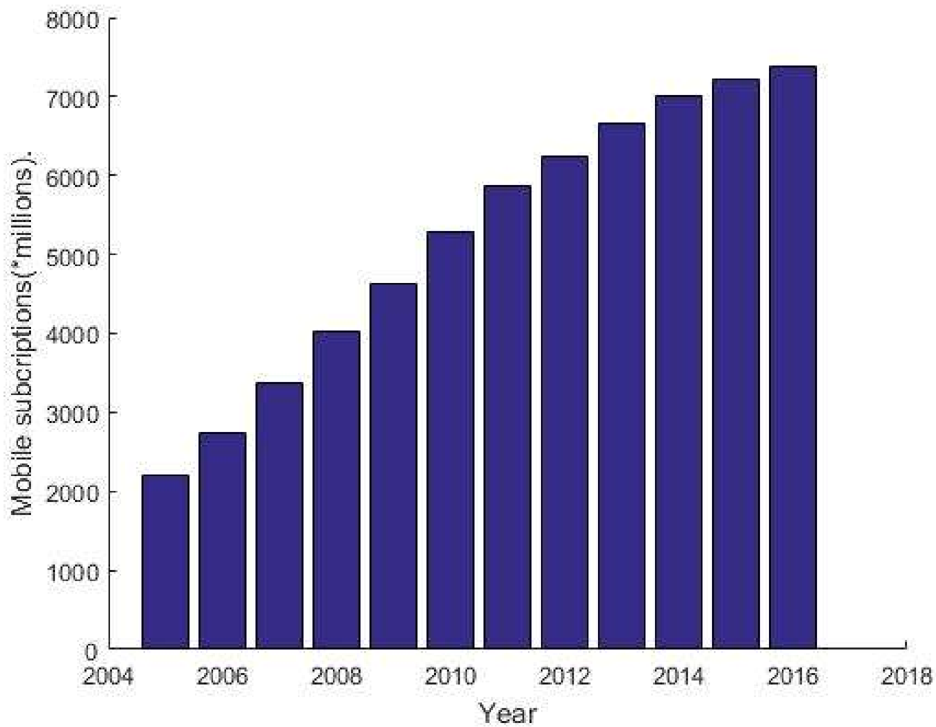

Figure 1.1. The yearly increase in mobile phone subscriptions.

According to [2], the number of mobile phone subscriptions are around 7.3 billion in 2016 but the actual number of mobile phone subscribers are close to 4.3 billion. This is due to the fact that a single person may own multiple subscriptions. As it is hard to get the unique subscriber statistics figure 1.2 shows the statistics of mobile subscriptions by regional population and the global percentage of subscribers as of 2016 [3]. The lower percentages in China, Africa and India can be can be due to many circumstances like lack of cellular coverage in certain parts of these regions. For example, in sub-Saharan Africa, approximately 30 % of the population live outside the cellular coverage [2].

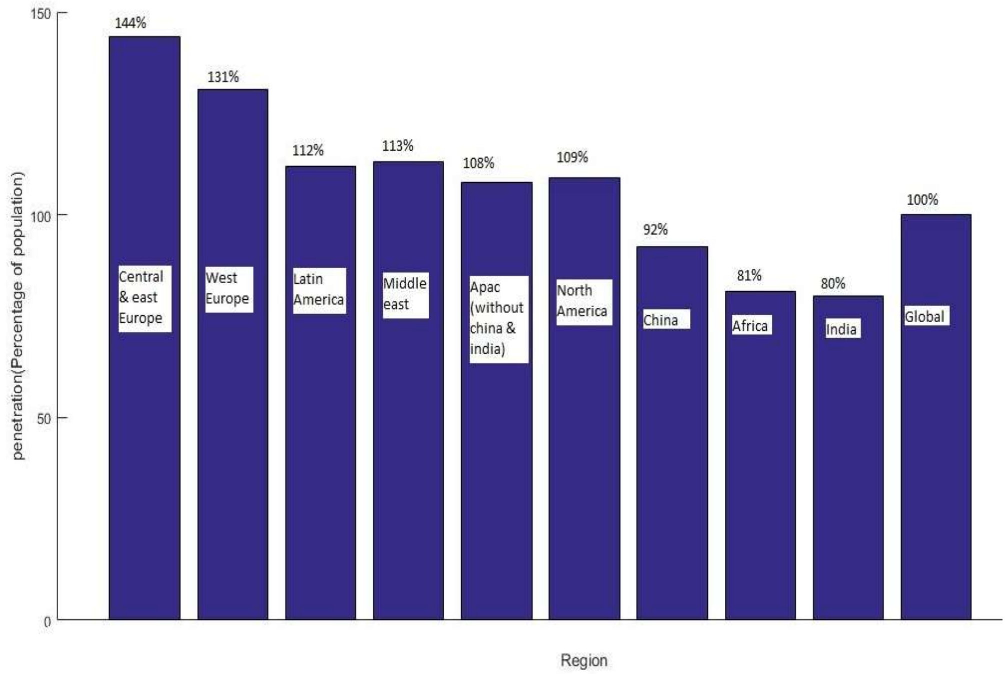

Figure 1.2. Regional penetration of mobile phone subscriptions.

Often this lack of cellular coverage is due to lack of access to the electricity grid for rural areas in the developing countries. In those areas, cellular coverage could be provided by powering mobile base stations (BSs) from alternative power sources. This incurs additional cost for laying out power infrastructure on the operator in parallel with the cellular network infrastructure [2]. However, these regions also represent immense opportunities of further growth for mobile network providers. As of the end of 2013, mobile-cellular subscriptions had reached their slowest-ever growth rates, at 2.6% globally, suggesting that the market is approaching saturation [1]. The cellular growth in developing regions has greatly outpaced that of developed regions. In the second quarter of 2014 alone, new mobile subscriptions in Africa and China reached about 20 million and 12 million respectively. While in North America and Western Europe the growth figures were only 2 million and 3 million respectively [2].

1.1 Powering mobile base stations.

Based on the availability of alternating current (AC) mains also called grid power in different locations powering options available to base stations can be categorized as

- Reliable grid power: AC mains serve as primary power source.
- Off grid power: no access to AC mains, alternative power sources are used.
- Bad grid power: there is access to the AC mains power, but it is not reliable and cannot be used as the primary power source.

About 80% of Africa and 30% of Asia falls into the category of underserved electrification scenario which leads to off grid and bad grid power situations for mobile BSs in these areas [2]. It is said that the total number of off grid and bad grid BSs in the world is around 1.02 million and it is expected to increase up to 1.18 million by 2020 [4]. Table 1.1 shows the statistics of off grid and bad grid BSs globally and the expected increase by the year 2020.

Table 1.1. Size of global off grid and bad grid mobile base stations [2].

Global estimates by region	2014			2020		
	Off Grid	Bad Grid	Total	Off Grid	Bad Grid	Total
South Asia	81800	176500	258300	94900	194900	289800
Sub Saharan Africa	145100	84300	229400	189100	106500	295600
Mena	0	69200	69200	0	76300	76300
Latin America	58400	265600	324000	62500	288400	350900
East Asia and pacific	34800	105400	140200	43300	12500	168300
Total	320100	701100	1021100	389800	791000	1180900

In these regions where the numbers of off grid and bad grid BSs are very high the alternative source of power that is predominantly used is the diesel power generators [2,3]. Using diesel generator (DG) is costly both in using diesel for power generation as well as the travel required to bring the diesel to the BS site. Some mobile service operators find that for some of these remote BSs energy provisioning consumes up to 50% of the total operational cost of these BSs [5]. In 2020 the greenhouse gasses (GHG) emission of the information and communications technology (ICT) sector will go up to 2% from 1.3% in 2007. The global GHG emission of the mobile ICT sector will be up to 0.5% of the total global GHG emissions [6].

1.2 Scope of thesis

Affordable access to mobile communication in all areas is considered to be an important component of social justice. It cannot be compromised due to economical reasons, similar to equal rights to other important resources for everyone like water, electricity and education. Low revenue per user and unavailability of grid power in remote areas compared with urban scenarios has been dragging down the deployments of mobile networks for years. With growing attention from governments and support from academia, the goal of this thesis is to motivate network operators to better drive cellular networks development in remote areas, by proposing and evaluating suitable energy sources for powering cellular BSs.

This thesis focuses on the power consumption of cellular BSs and proposes alternate energy sources to power the BSs that do not have grid power easily available. This can provide solutions for the network operators to expand their infrastructure in order to provide cellular connectivity to the users in the remote areas. The major source of power consumption in a cellular network is the BS. So this thesis will review the structure of a cellular BS in order to gain an understanding of the power consumption of BS and its components and how the BS power consumption affects the cellular network. The thesis will throw light on the previous efforts to lower the power consumption of mobile BSs. Utilizing those approaches to what extent the power consumption can be lowered and how much power savings can be achieved. We will also discuss the renewable power sources (wind and solar) and their availability in different regions to use them powering mobile BSs. In case of solar energy regions of different latitudes are considered for analysis. The regions at low latitudes such as African countries like Nigeria, Congo etc receive more solar irradiation compared to the regions at high latitudes like arctic regions such as Nunavut, Canada. Similarly, average wind speeds for different regions and analysis of energy production for these windspeeds using small wind turbines is presented. This will help in understanding that whether renewable energy sources are adequate to power BSs and what would be the requirements for renewable energy systems in those regions. The use of renewable energy resources will help to replace or reduce the usage of diesel fuel. This would help operate the mobile BSs in remote areas to provide connectivity where it is not possible to provide coverage because of operational costs associated with off grid BSs.

1.3 Outline of the thesis

The thesis consists of 7 chapters that are arranged as follows: chapter 1 gives an introduction about the thesis, chapter 2 throws light on the power consumption of mobile ICT sector and the role of BS in the power consumption of a cellular network. It throws light on the power consumption of structural components of the mobile BS. Chapter 3 discusses the various approaches proposed that can lower the power consumption of a BS and it introduces two key technical components of the 5G cellular access network which can reduce the power consumption of the BS. Chapter 4 discusses the renewable energy resources in different regions which can be used to power the BSs as an alternate to the grid energy. Chapter 5 proposes the alternate energy solutions that could be utilized for cellular BSs in remote areas. Finally, discussion for future work and the thesis summary are presented in the chapters 6 and 7.

2 BASE STATION ENERGY CONSUMPTION

The major source of energy consumption in a cellular network is the base station and according to [7] BSs consume up to 80% of the total cellular network energy consumption. Figure 2.1 shows the average energy consumption of different elements of the cellular network in a year. It can be seen that the power consumption of BSs is much higher compared to power consumption of all the other elements combined. Other elements in cellular network consists of the user equipment (UE), network controllers, and core and servers that use 4%, 1% and 15% of the networks power respectively.

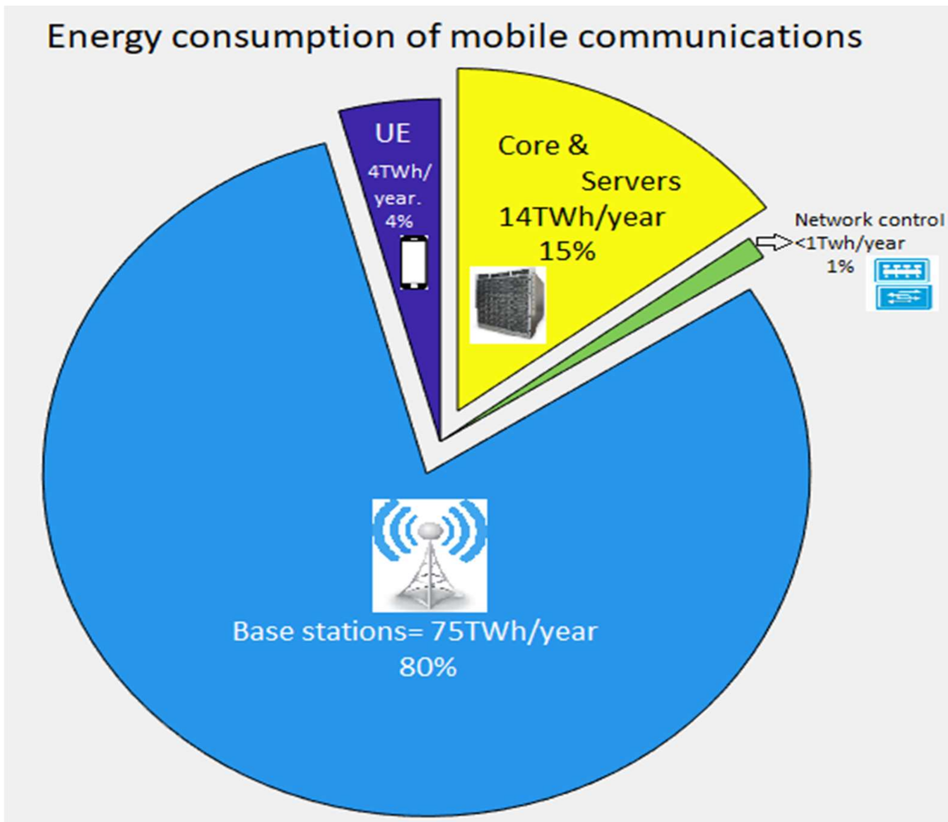

Figure 2.1. Per annum energy consumption of mobile communications.

The power consumption of a base station depends on the base station type that includes femto, pico, micro and macro base stations which are differentiated based on their coverage area. Table 2.1 shows the typical power output of each of these base stations and their coverage area.

Table 2.1. Characteristics of different base stations [8].

Base station type	Coverage area	Output power	Typical use
Femto	10 m	20-100 mW	Home or office use
Pico	100-200 m	250 mW	Home, office, factory
Micro	1-2 km	2-10 W	City, block, buildings
Macro	5-32 km	40-100 W	Rural, suburban, urban

In this thesis, a macro base station is considered because the off grid base stations and bad grid base stations are usually located in areas where the number of subscribers is less compared to urban areas. So macro base stations with large coverage areas is the preferable choice for mobile communications in these areas.

2.1 Base station functional components

A base station is a device needed to communicate with the mobile stations and the backhaul network. A base station consists of different power consuming components which are shown in figure 2.2. These components can be divided into two categories. The first category consists of the equipment that are used per sector such as digital signal processing, power amplifier, transceiver and the rectifier. The power amplifier transceiver and the rectifier can be incorporated in the baseband unit along with the digital signal processor. Or these can be separate located inside remote radio head (RRH) situated very close to the antennas and are connected to the base band unit with optical fibres [9]. The other category includes the equipment that is common for all the sectors such as cooling, and the microwave link station used for backhauling.

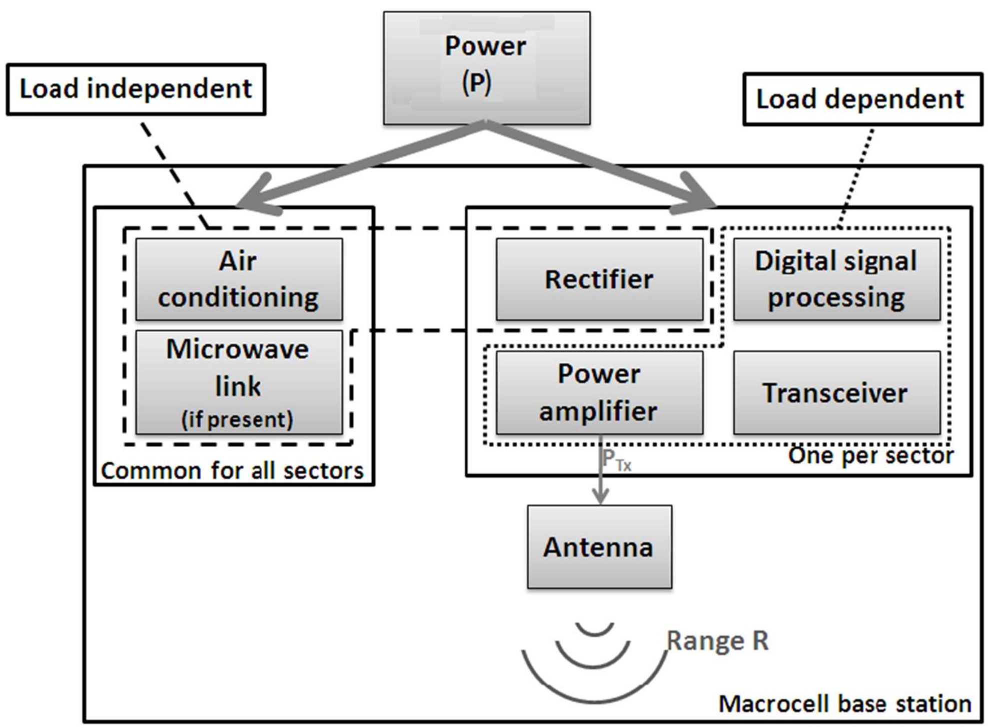

Figure 2.2. Base station functional components.

Figure 2.2 shows the structural breakdown of a cellular base station. A brief description of the components of the base station is presented underneath,

Digital signal processing:- deals with converting the signal into a sequence of data bits or data symbols and the processing of these bits or symbols.

Transciever:- is responsible for transmitting and receiving the signals.

Power amplifier:-converts the input direct current (DC) power into a significant radio frequency (RF) signal.

Air conditioning:- Controls the temperature of the cabin in which the base station is located.

Microwave link:- is used for communication with the backhaul network (Can be replaced with a fibre link).

2.2 Power breakdown of base station

The power consumption of base station consists of two independent contributions. The first contribution is independent of the traffic load and is the power required for the base station to be in standby mode ready to accept any traffic and serve any user at any time. Until recently this component amounted to roughly 1 kW of continuous power dissipation [10]. The second contribution is from the traffic load at any given time. This part of energy consumption is variable and could be any value from 0-500 W [10]. The total power consumption of the base station is the sum of these two components at any time. Figure 2.3 shows the power consumption of a base station during 7 days of a week. The figure shows that the varying power consumption levels are due to the traffic load. When the traffic is high in the network the base station use more energy and less when there is low traffic.

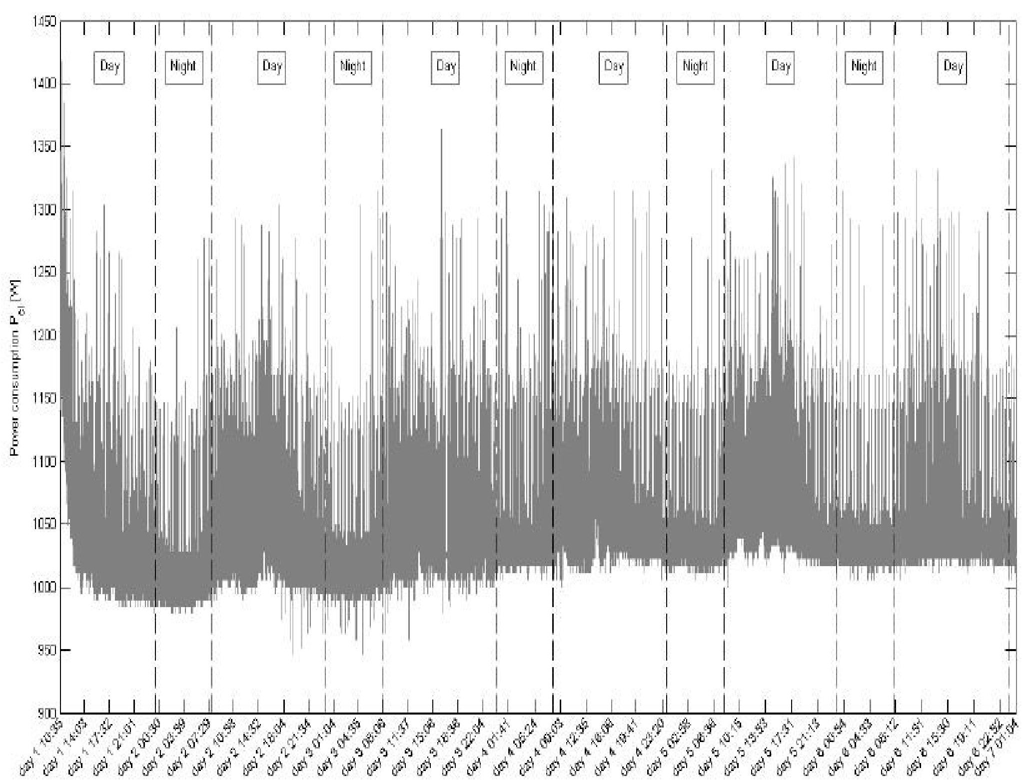

Figure 2.3. Evolution of power consumption in time [10].

The power consumption of BS functional components is illustrated in figure 2.4. It shows that only 6% of the total power dissipated by the base station is transmitted into the air for downlink communications at the antennas. This points to the remarkable inefficiency of the mobile base stations and therefore the need to make base stations more power efficient.

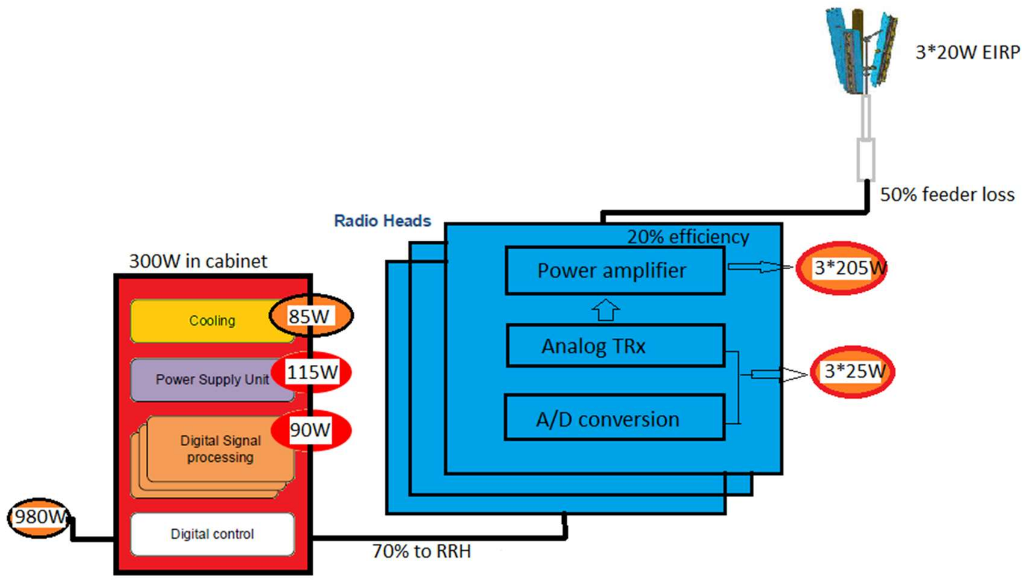

Figure 2.4. An example of base station power breakdown [7].

Fig 2.4 shows an example of the power consumption of the individual components of a base station. A more general and widely accepted power consumption model of the macro base station is shown in Fig 2.5 that shows both components of base station power consumption. The first one is the base station power consumption in the standby mode when there is no traffic. And the other is the base station power consumption in the presence of load (with traffic).

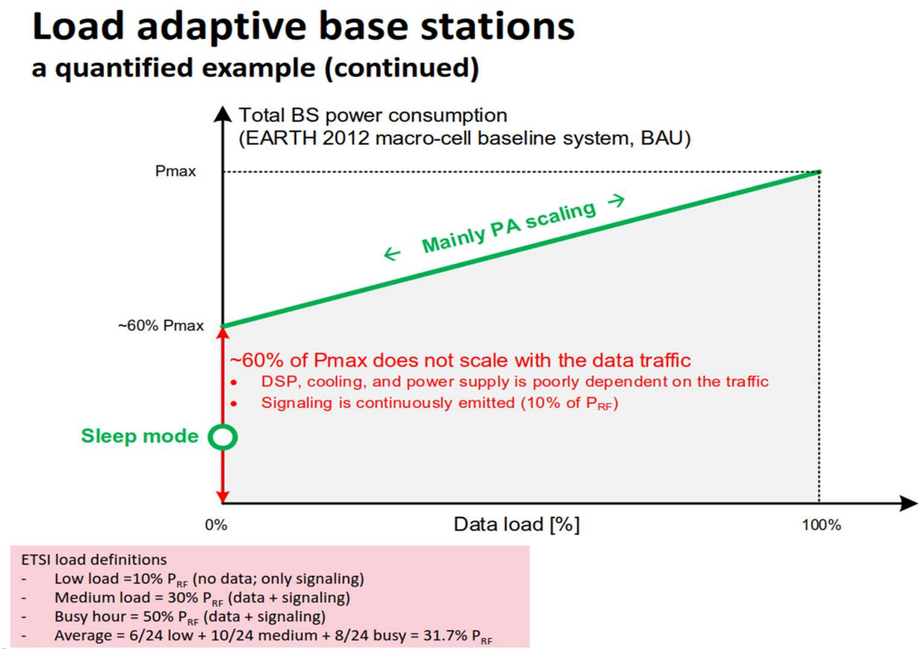

Figure 2.5. Power dissipation of base station with traffic load [11].

In no load, the base situation consumes 60% of the maximum power consumption in order to provide signalling. This signalling consists of pilot signals to detect the user and to provide communications when needed but no data is transmitted. At medium load and maximum load, the power increase is attributed to data transmission in downlink and continued signalling. A base station provides signalling at all times but when data is transmitted in downlink the power consumption increases based on the traffic load.

2.3 Power model of base station

In this section, a mathematical model for the power consumption based on [7,10,12] is presented. Figure 2.6 shows the power flow in a base station among its structural components.

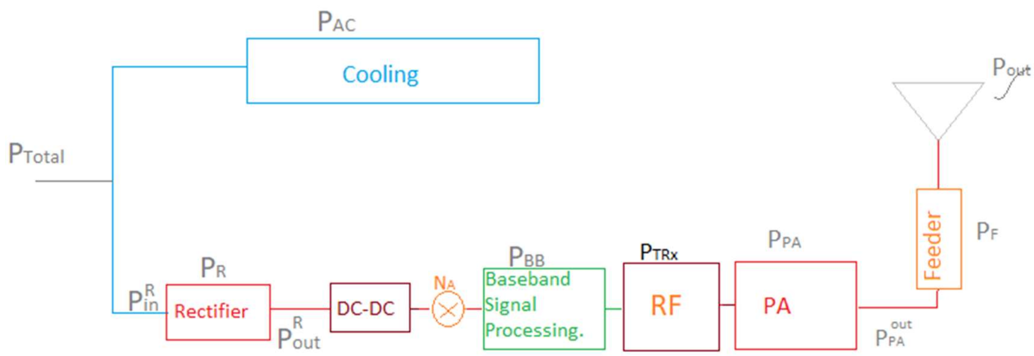

Figure 2.6. Power flow diagram of the base station.

The following notations are used for the devices in fig 2.6. For a device X, the power consumed by it is denoted by P_x. P_{in}^{x} and P_{out}^{x} denote the input and the output power of the device X. N_A denotes the number of sectors in the base stations. Underneath a brief description about the efficiency and power consumption of these components is presented that would help in understanding and deriving the mathematical model for the total power consumption of the base station.

2.3.1 Rectifier and DC-DC

The efficiency of a rectifier is about 92% for a conventional rectifier and for the latest products it is about 97% when the average load is between 40-90% [12]. The power consumption of a rectifier i.e. the power that is dissipated as heat depends on the rectifier efficiency and the output power from the rectifier. The power loss factor of the rectifier is given by the following equation (2.1),

$$\sigma_R = 1 - \eta_{dc} \ , \tag{2.1}$$

where $\eta_{dc} = \frac{P_{out}^{R}}{P_{in}^{R}}$ is the efficiency of the rectifier, similarly the power loss factor in the dc-dc power supply is given as

$$\sigma_{dc} = 1 - \eta_{dc} \ . \tag{2.2}$$

2.3.2 Baseband signal processing

The base band digital signal processing unit is considered to have a constant power consumption [12]. This power is denoted by P_{BB} and its value lies in the range of 80-150 W varying for different base stations depending on the manufacturer.

2.3.3 RF transceiver

The radio frequency (RF) transceiver consists of a receiver and a transmitter for uplink and downlink communications. The linearity and blocking requirements of the transceiver differ significantly for different base station types and therefore different architectures are used based on these requirements.

2.3.4 Power Amplifier

An amplifier magnifies the amplitude of an RF signal. The power dissipated in power amplifier (PA) is given by

$$P_{PA} = \frac{P_{out}^{PA}(1-\eta_{PA})}{\eta_{PA}}, \tag{2.3}$$

where η_{PA} denotes the efficiency of the power amplifier. Traditional PAs have an efficiency that could be any value between 5-20%. However, it can be improved by special design techniques such as digital pre distortion (DPD), Doherty power amplifier and envelope tracking (ET) which can lift the power efficiency up to 70% [13] depending on the physical structure of signal and performance requirements.

2.3.5 Feeder

Feeder is the cabling system that connects the base station with the antennas, conventionally the antenna and base stations are a few meters apart and are connected through a coaxial cable. The signal attenuation of coaxial cable feeder is about 3 dB. Nowadays remote radio heads (RRH) are used [14]. RRH are small cabinets that hold the RF equipment and are placed very close to the antennas and they are connected to the baseband processing unit with optical fibres. The efficiency of a feeder is

$$\eta_F = \frac{P_{out}}{P_{out}^{PA}}. \tag{2.4}$$

The efficiency approaches 1 when RRH is used and 0.5 when the coaxial cabling is used.

2.3.6 Cooling

Electronic equipment have specific operating temperatures and in order to keep the temperature of most components of a base station within the specified range, cooling is needed which is often provided by air conditioners (A/C). As stated in [15] A/Cs requires as much as one third of the total power dissipated in the form of heat. The power consumption of A/C system can be modelled as

$$P_{AC} = \left[\frac{P_{in}^{R}-500- \quad {out}}{3}\right]^{+}, \tag{2.5}$$

where the notation $[X]^{+} = \max(X,0)$ is used because base stations operating under 500 W usually do not require A/Cs for cooling so P_{AC} value will be zero for them.

2.3.7 Total Power consumption

Looking again at figure 2.6, it can be seen that the total power consumption of BS is the sum of the input power of rectifier and the power flowing into the A/C. It can be written as

$$P_{total} = P_{in}^{R} + P_{AC} \ , \tag{2.6}$$

where P_{in}^{R} is the input power of the rectifier which comprises of the input power of PA, BB, DC-DC, feeder and the transceiver.

$$P_{Total} = N_{TRx} \cdot \frac{\frac{P_{out}}{\eta_{PA} \cdot \eta_{F}}}{(1-\sigma_{dc})(1-\sigma_{R})} + P_{BB} + P_{TRx} + \left[\frac{P_{in}^{R} - 500 - P_{out}}{3}\right]^{+}, \tag{2.7}$$

where $\sigma_{DC} = \frac{P_{dc} * 100}{P_{in}^{dc}}$ and $\sigma_{R} = \frac{P_{R} * 100}{P_{in}^{R}}$ represents the percentage of power lost in the rectifier and the dc-dc converter.

3 REDUCING BASE STATION ENERGY CONSUMPTION

In the recent years, numerous research is being done by academia and industry in order to seek new ways to reduce the energy consumption of the cellular networks sector to make it ‘green’ and cost efficient. As a result, various energy efficient solutions have been investigated. Discussed earlier in chapter 2 the major source of energy consumption in a cellular network infrastructure are the BSs. Therefore, reducing the BSs energy consumption would significantly lower the overall cellular network’s energy consumption.

Various approaches to reducing the energy consumption of BSs were identified in previous research. These proposed approaches can be classified as 1) Improving energy efficiency of BSs at the component level, 2) Introducing sleep modes, 3) Optimizing energy efficiency of the radio transmission process and 4) Planning and deploying heterogenous small cell networks.

From the energy perspective, the performance of the BS components is unsatisfactory and various research papers have been published that focus on addressing these issues. Studies to improve the energy efficiency of the base station components have focused on the power amplifiers used in the base stations because PAs consume most of the energy supplied to the base station. PAs with digital pre distortion (DPD) Doherty architecture and GaN based PAs can boost the efficiency of the amplifier to over 50%. Shifting from traditional RF analog amplifiers to switch mode based PAs the efficiency of the power amplifiers can be increased up to 70% [16]. Another way to reduce BS power consumption is by reducing the feeder loss between the power amplifier and antenna. Usually, coaxial cable is used to connect PA with the antenna which adds 3 dB i.e. 50% loss to the power transmission. This can be avoided by designing the base station in a way that PA is very close to the antenna and using low power RF cables.

Energy savings can be achieved in the BSs by switching the base stations to sleep mode otherwise referred to as idle mode or low power mode during low traffic conditions. Sleep modes generally involve turning off selected components of the BS such as power amplifiers, signal processing units or cooling equipment [17].

Optimizing the energy efficiency of the radio transmission process using advanced techniques such as multiple input multiple output (MIMO), cooperative relaying, cognitive radio, channel coding and resource allocation for signalling can result in reducing the BS energy consumption [17].

Macrocells are designed to cover large area, therefore macrocells are less efficient in providing high data rates and less energy efficient. One way to maintain high data rates to users is to decrease the cell size i.e. minimize the propagation distance between the BS and UE. Reducing the propagation distance between BS and UE would also reduce the transmit power of the BS and thus increase the energy of efficiency of the BS. This can be achieved by deploying heterogenous cellular networks based on smaller cells such as micro, pico and femtocells. A typical heterogenous network is shown in figure 3.1 [18].

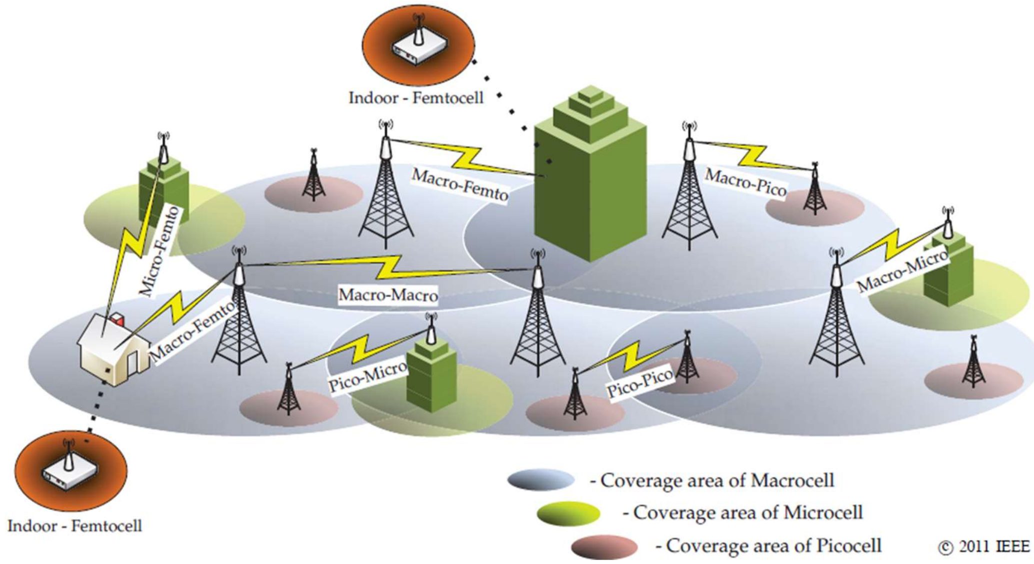

Figure 3.1. A typical heterogenous network (© 2011 IEEE).

Smaller cells due to their size are much more power efficient in providing mobile broadband coverage. Simulations show that a joint deployment of pico and microcells with only 20% customers having picocells could result in an overall 60% reduction in energy consumption compared to a network with microcell only [18].

Table 3.1 list the reported energy savings that could be achieved by implementing some techniques discussed above for reducing BS energy consumption [18].

Table 3.1. Energy savings by some of the discussed techniques (© 2011 IEEE).

Description	Reported energy savings
Improvements in power amplifiers	50% with GaN based Doherty architecture 70% with switching based amplifiers
Network self-organizing techniques	20-40% base station power savings
Heterogenous network deployment	Up to 60% compared to network with macrocells
Dynamic spectrum management	Up to 50%

3GPP release 14 has marked the start of the 5G wireless access scheme which is the successor to the 4G long term evolution (LTE) scheme. 5G wireless access addresses the energy inefficiency of the 4G LTE. At 2.6 GHz spectrum using carrier aggregation with LTE, 5G will provide throughput greater than 100 Mbps and 35% power reduction compared to the 4G LTE power consumption. At expected traffic levels beyond 2020 5G operating at 15 GHz frequencies can reduce the BS power consumption by 50% and will provide 10 times more capacity [19]. Two key features of 5G wireless access scheme that are of particular interest in this scenario i.e. reducing BS station power consumption to enable installation and operation of cellular communications in the off grid and bad grid sites are

- Beamforming through massive MIMO or UE specific beamforming gives very high beamforming gain because of large antenna arrays which can be used to provide higher data rates at longer distances. Investigated in [19] increased gain can provide additional link budget that helps to reduce the BS power consumption. Also, higher transmission speeds using massive MIMO allows for longer sleep modes in BSs [20].

- Ultra lean design to enable longer sleep modes will enable BSs to sleep for longer consecutive durations, therefore, reducing energy consumption compared to LTE.

3.1 Energy reduction through beamforming

Overall 5G wireless access consists of two key components, backwards compatible LTE extension operating on existing spectrum and new radio access spectrum at high frequencies above 6 GHz for high bandwidth availability. At high frequencies, the propagation is more hostile meaning increased propagation losses in free space and increased penetration losses and diffraction losses. But higher frequencies also open up new doors to implement advanced antenna technologies. At higher frequencies the size of the corresponding antenna elements decreases and in a small area more antenna elements can be packed. For example, an antenna operating at 2.6 GHz is approximately 1 m tall and it contains 20 elements and at 15 GHz it is possible to design an antenna with 200 elements, but it would be only 20 cm tall and 5 cm wide [21].

Path loss between transmitter and receiver does not change with increased frequency if the effective antenna aperture does not change. But the antenna aperture reduces with increase in frequency which can be compensated by increasing the number of antenna elements so that the effective aperture stays the same. Packing higher number of antenna elements in an area facilitates the formation of the narrower beam. Narrow beams make it easier to steer the beams to intended users to maximize useful signal strength and reduce the interference to other users. Figure 3.2 shows the basic concept of UE specific beamforming proposed in the 5G wireless access scheme.

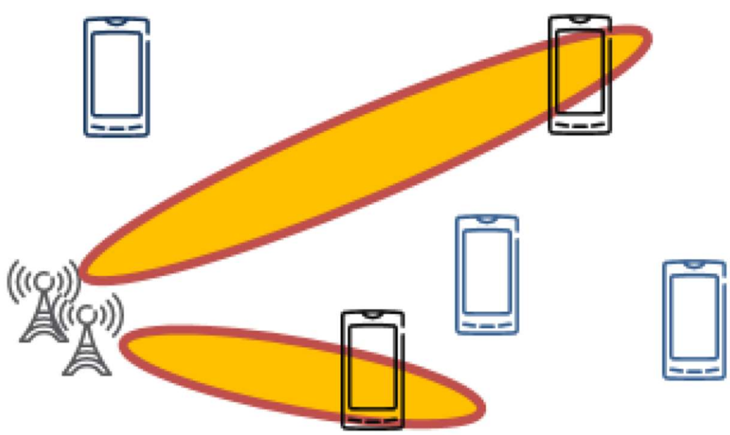

Figure 3.2. User Specific beamforming.

A simple model to illustrate the mapping of antenna pattern to the beamforming gain is

$$G_{Beam} = \frac{A_{spher}}{A_{Beam}} = \frac{16}{sin\theta \times sin\varphi}\ , \tag{3.1}$$

where 'θ' denotes the azimuth half power beamwidth angle and φ denotes the elevation half power beamwidth angle shown in figure 3.3. From equation (3.1), it can be seen that the gain of the beam is an inverse function of the azimuth and elevation half power beam width angle. So narrower beam means smaller azimuth and elevation angles and therefore increased beamforming gain.

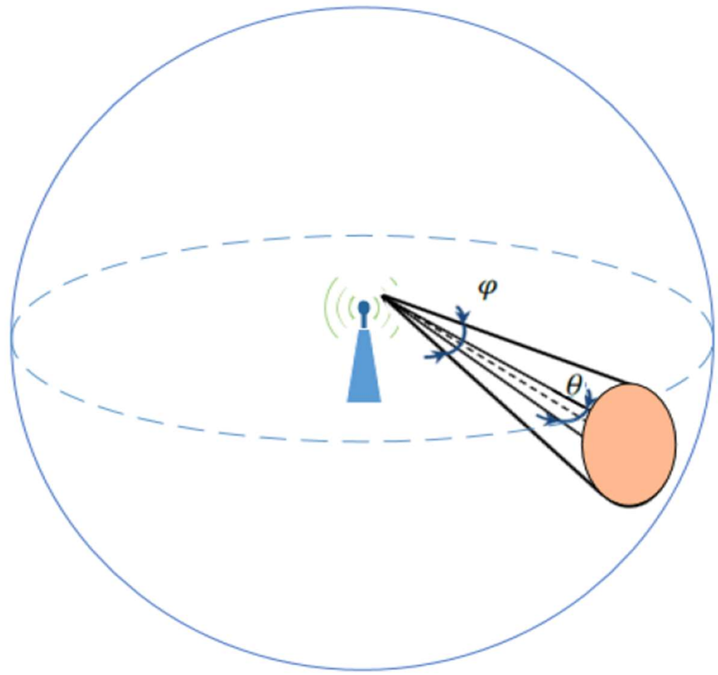

Figure 3.3 Antenna pattern as an elliptical area.

A beamforming model based on a grid of beams (GoB) is discussed in [20] that creates GoB by applying azimuth discrete fourier transform (DFT) vectors to the antenna rows and elevation DFT vectors to the antenna columns. The beam selected for communication will have the highest beam forming gain whose gain can be calculated by

$$G = w^H R w\ , \tag{3.2}$$

where 'w' denotes the weight vector of the selected beam and 'R' denotes the channel covariance matrix between the base station antenna elements and the first UE antenna. GoB antenna gain increases linearly with the number of antenna array e.g., 4 antenna array will have GoB gain of 5-6 dB and an array with 8 elements will have GoB gain of 8-9 dB [22].

Massive MIMO antenna arrays can produce high performance narrower beams for cellular communications. These high performance beams can reduce the power consumption of the base station and increase the capacity of the system [19,20]. They can also be used to increase the size of the cell and allows for deployment of ultra large cells (over 50 km) [23]. Large cells with energy efficient radio transmission through beamforming can be particularly ideal for the off grid and bad grid base stations.

Because the number of UEs is less in these sites compared to the dense urban cells and alternative sources of power supply are used.

3.2 Energy reduction through ultra-lean design

In a cellular network, all the transmission signals are not used for data transmission. In LTE transmission the BSs are required to transmit pilot signals at least once during every 1 ms. The structure of an LTE downlink frame is shown in the figure 3.4. It shows the allocation of different synchronization signals and control and system information channels that allow UEs to find and connect to the network.

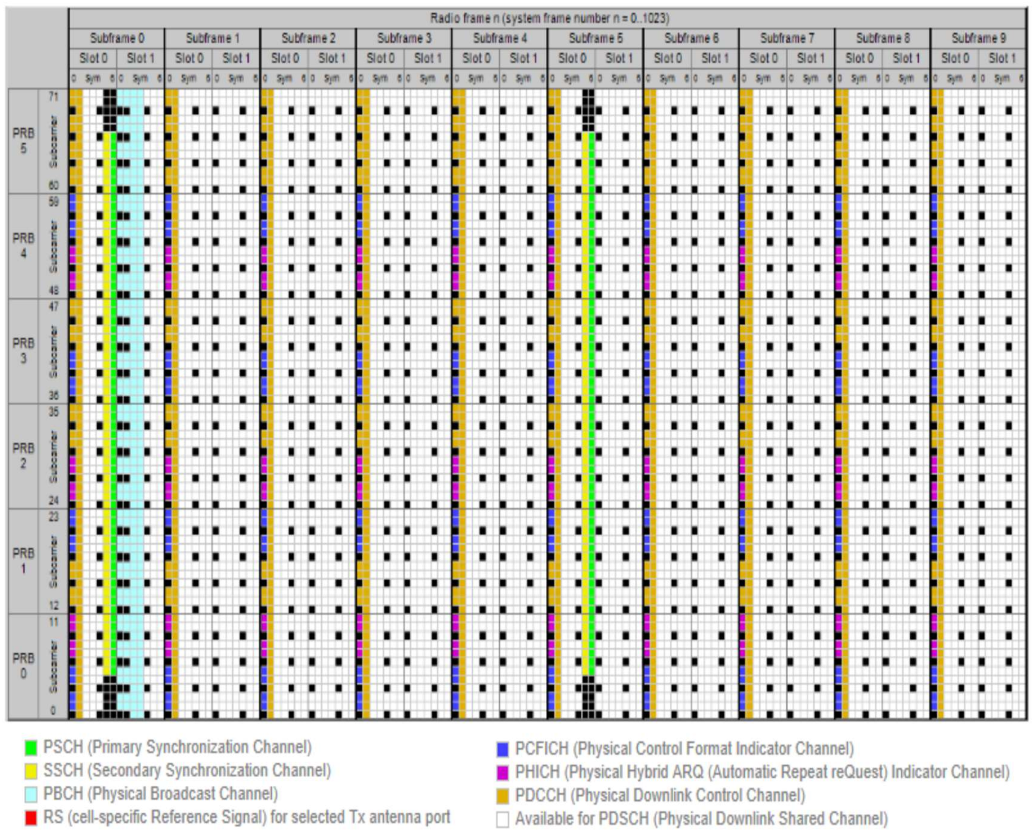

Figure 3.4. LTE downlink frame structure [24].

An ultra-lean system design helps to extend the benefit of beamforming by replacing the broadcast that cannot be utilized by UE specific beamforming with dedicated signalling [20]. It also contributes to more energy saving by introducing discontinuous transmission (DTX) at the BS side.

DTX is a power saving protocol that puts the BS to sleep when there is no data to transfer to reduce idle time power consumption [25]. Sleep mode momentarily powers down the device to save power while remaining connected to the network with reduced throughput. This could be done by disabling some components that are not needed. In cell DTX technology the cell is not completely switched off when the BS is in sleep mode. The evaluated capacity of sleep mode depends on the consecutive empty transmission durations called DTX duration. In LTE systems there is a comparatively large number of mandatory transmission signals and the DTX duration for LTE is 0.2 ms [26]. The cell DTX factor for LTE is estimated to be 0.84 [20]. With ultra-lean design, the DTX duration can be extended to 100 ms [20] due to minimization of non-data transmission signals and the DTX factor can be reduced to 0.29 [20]. The cell DTX factor represents the capacity to save energy by reducing the power consumption of BS in idle mode.

Using the Earth power model [7] for power consumption of LTE BS along with taking into account the cell DTX factor to compute the LTE BS power consumption is given by [20]

$$P_{BS}^{LTE} = N_{tx} \begin{cases} \Delta_p P_{tx} + P_o & \text{when BS is transmitting} \\ P_o & \text{when BS is inactive} \\ \delta P_o & \text{when BS is not transmitting} \end{cases}, \tag{3.3}$$

where N_{tx} denotes the number of transceivers in the BS and P_{tx} denotes the power radiated from each transceiver. In this expression 'δ' denotes the cell DTX capacity which is in the range $0<\delta<1$.

Ultra-lean design of macro BSs holds the promise for low energy consuming base stations in the future. This could make deployments of BSs easier in those off grid and bad grid sites where cellular network operators are reluctant to extend their coverage because of high operational costs due to use of alternative energy sources required in those areas. The ultra-lean design is a key aspect of the upcoming 5G wireless access technology that promises energy efficiency, very high capacity and data rates with the promise of low cost.

4 RENEWABLE ENERGY

In this section, we will discuss the renewable energy resources that can be used to power off grid base stations in remote locations. There are a number of renewable energy resources that are used to produce electrical energy such as solar energy, wind energy, geothermal energy, tidal power etc. But unlike other resources solar and wind energies are the renewable resources that are available everywhere, for example, tidal power is only available near seashores. Therefore, wind and solar energy are considered here as alternate renewable sources to grid power for BSs.

4.1 Solar energy

Solar energy is an unlimited source of energy that can be used to produce electrical energy. Producing electrical energy from solar irradiation varies depending upon the geographical location of particular regions as solar irradiation differs for different regions. Figure 4.1 shows the solar irradiation of different regions all across the world.

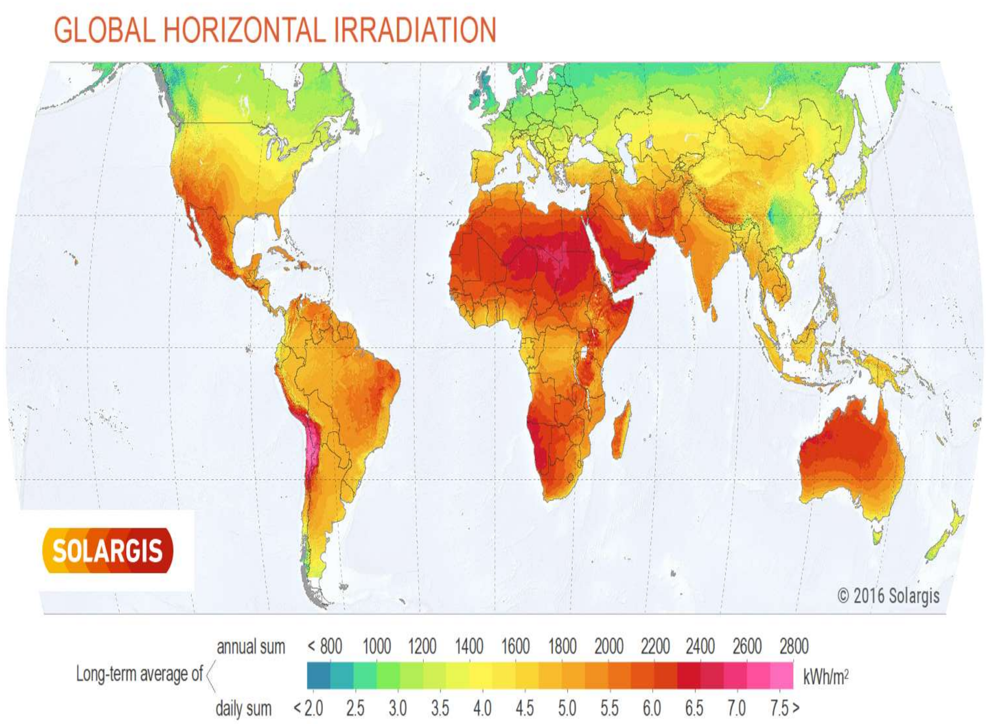

Figure 4.1. World solar irradiation map (GHI solar map © 2017 Solargis) [27].

Figure 4.1 shows the horizontal solar irradiation for the different regions. The regions are separated based on their colour codes which describes the average yearly or daily solar irradiation received in these areas. Irradiation arriving the surface of solar panels depends on environmental factors most important of which is the air mass and solar irradiation that differ year by year for each region.

In this report, different regions with irradiation levels of high contrast are discussed to deduce if the deployment of solar energy is a viable source for powering mobile base station terminals. Underneath the solar energy resources for four different locations Seinajoki Finland, Nunavut Canada, Girara Indonesia and Sokoto Nigeria are viewed. The location of these regions is shown on the world map in figure 4.2.

Figure 4.2. Location of the regions considered for analysis (© Copyright Graphics Factory CC).

Figure 4.2 shows the regions for which the solar irradiation levels are discussed here. As seen from the figure Nunavut and Seinajoki are located at higher latitude towards the north with Nunavut further towards the north and Girara and Sokoto are located at low latitude. The solar irradiation data for each of these locations is shown in figure 4.3 [28,29,30].

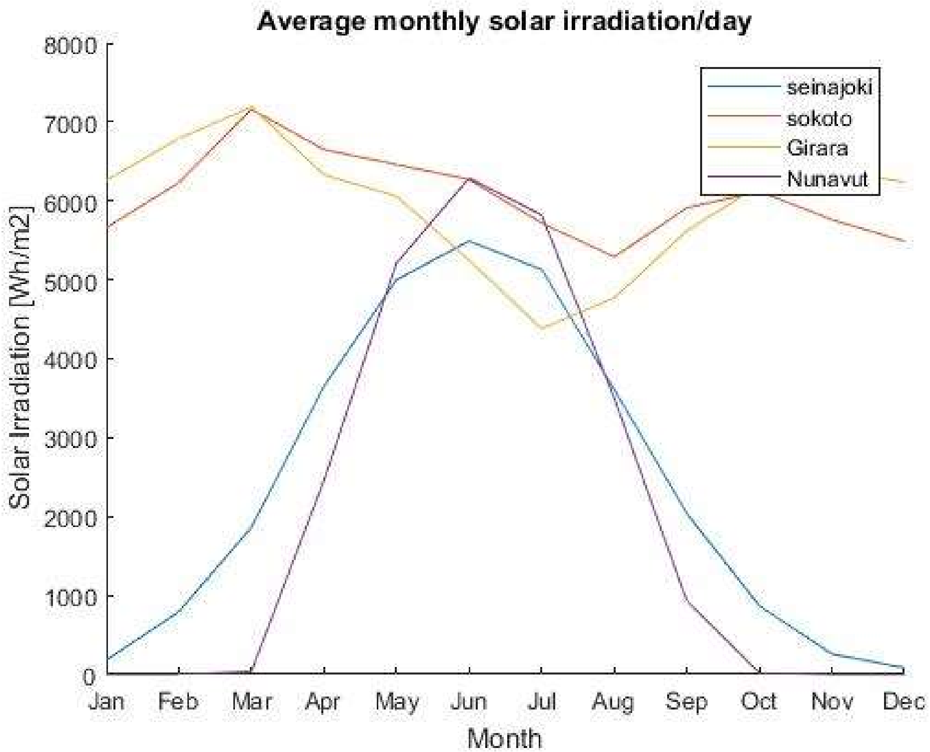

Figure 4.3. Average irradiation/m^2/day for different locations.

Figure 4.3 shows the variation of solar irradiation in the chosen regions due to the geographical location of these regions. The values presented in the figure are average values per day for every month, but the real daily irradiation may differ compared to the average. The regions that lie near the equator receive the most solar radiation and moving to higher latitudes towards the north pole and south pole the average solar irradiation decreases. It can also be seen that some regions get high amounts of solar irradiation for almost the entire year but in some regions, the solar irradiation varies tremendously in a year and during some months the solar irradiation is almost close to zero or a very small value.

4.2 Case studies for different regions

In this section, a brief case study for electrical power generation from solar irradiation of the example regions discussed in figure 4.3 is done to analyse the amount of energy that can be harnessed based on their average solar irradiation data for solar installations of different photovoltaic (PV) capacities.

4.2.1 Sokoto, Nigeria

For Sokoto, Nigeria the average solar irradiation per day during the 12 months of the year are presented in figure 4.2. It can be seen that in this region the solar radiation levels are high which represents solar energy as a very viable and feasible source for powering mobile base stations. The solar radiation levels in Sokoto average almost

5850 Wh/m2 [29] per day. Figures 4.4 and 4.5 show the solar irradiation data and the maximum energy output that can be produced by two example photovoltaic installations (see section 4.3) of 1 kW and 5 kW capacity for Sokoto, Nigeria

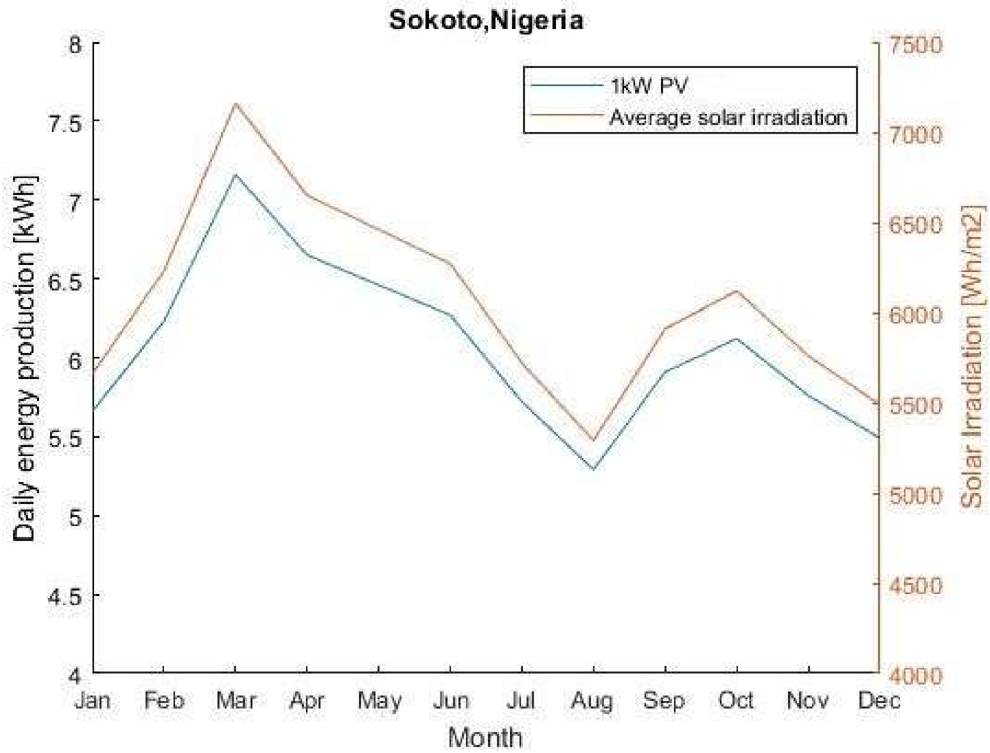

Figure 4.4. Average solar irradiation and energy produced for 1 kW PV installation.

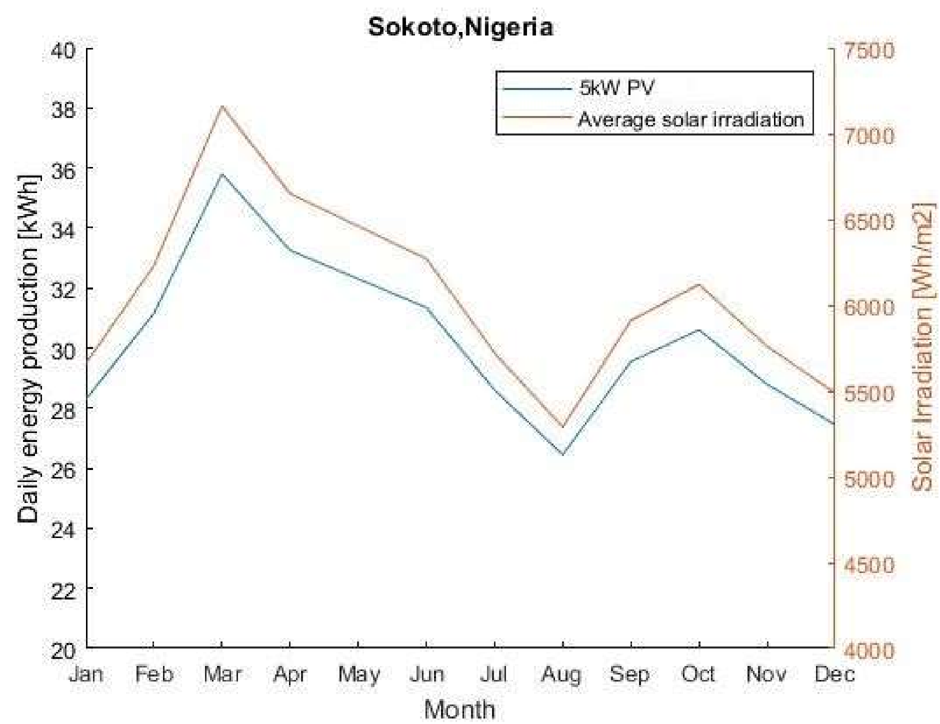

Figure 4.5. Average solar irradiation and energy produced for 5 kW PV installation.

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4.2.2 Girara, Indonesia

In Girara, Indonesia the average solar irradiation during the 12 months of the year can be seen from the figure 4.2. Similar to Sokoto discussed above it can be seen that this region also has high solar radiation levels. It shows that this region is also a place where solar energy is a feasible choice for powering mobile base stations in off grid sites. The solar irradiation in Girara average almost 5950 Wh/m2 per day [29] which is very close to the value we discussed in case of Sokoto. Figures 4.6 and 4.7 show the solar irradiation data and the energy that can be produced by photovoltaic installations of 1 kW and 5 kW for Girara, Indonesia.

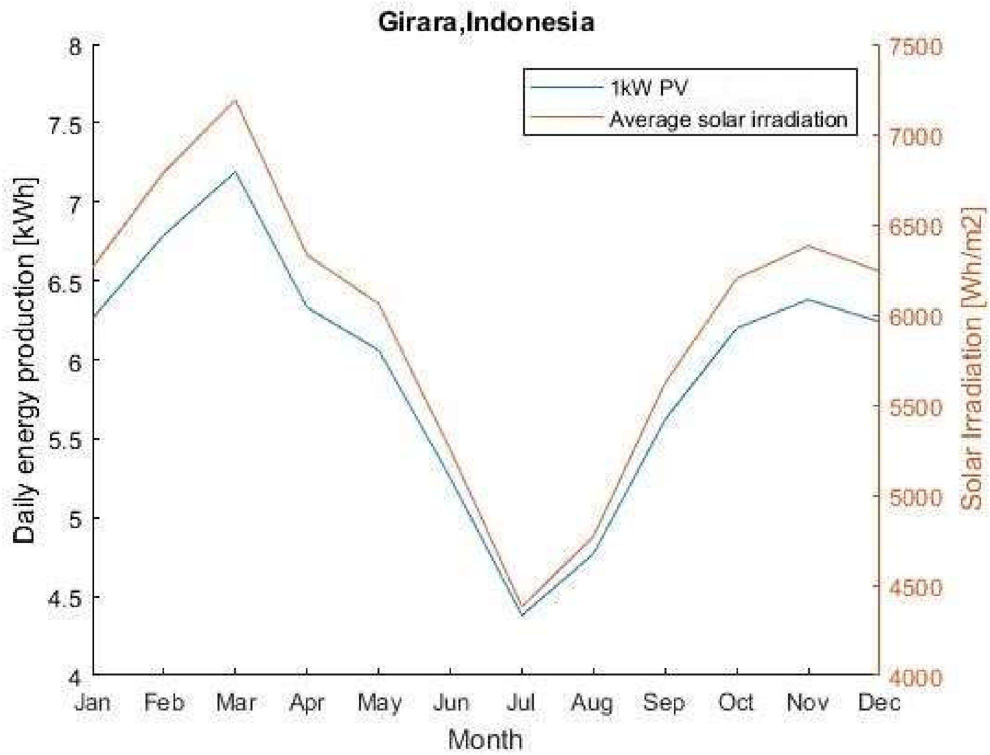

Figure 4.6. Average solar irradiation and energy produced for 1 kW PV installation.

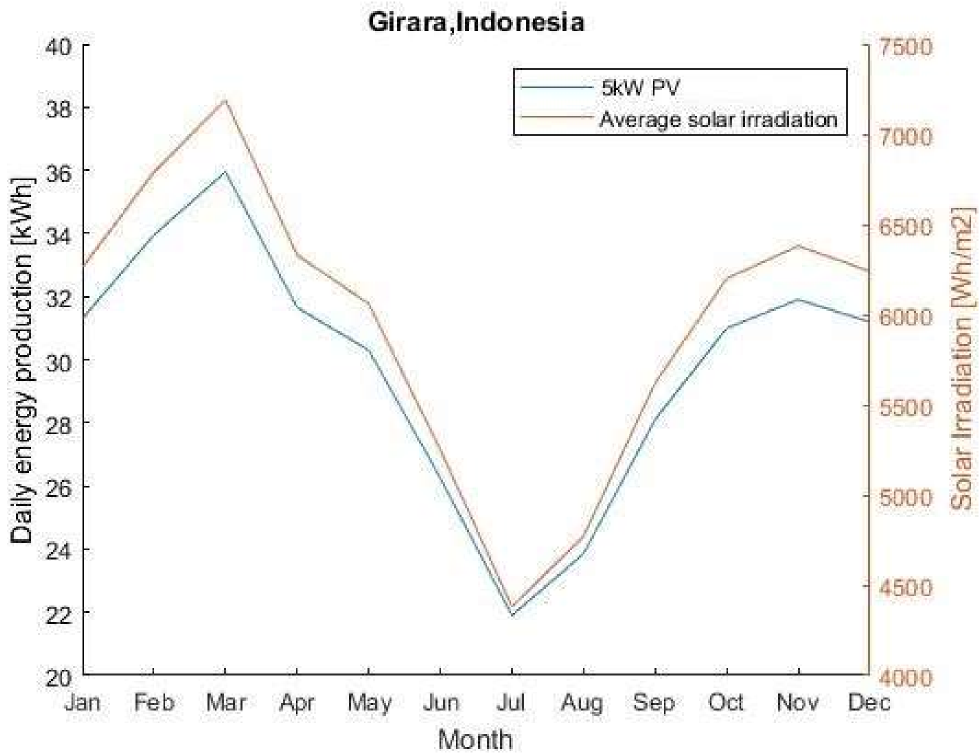

Figure 4.7. Average solar irradiation and energy produced for 5 kW PV installation.

4.2.3 Seinajoki, Finland

In Seinajoki, Finland the average daily irradiation for the year is almost 2420 Wh/m2 [28] which is small compared to the regions discussed above. This is due to the geographical location of this region, as the daily sun hours in this region are low due to the high latitude of the region and the closeness towards the North Pole. In Seinajoki, Finland besides less daily radiation levels the regions experience the months during which there is no sun or very little irradiation for days or even months for the period of November to February. Figures 4.8 and 4.9 show the solar irradiation data and the energy that can be produced by PV installations of 1 kW and 5 kW for Seinajoki, Finland.

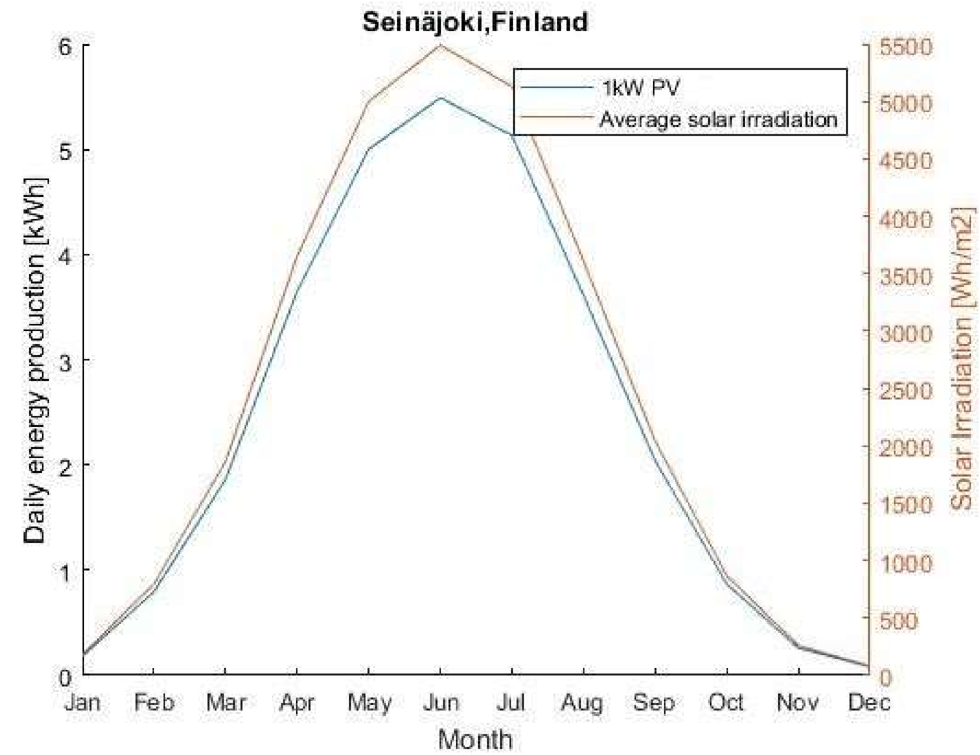

Figure 4.8. Average solar irradiation and energy produced for 1 kW PV installation.

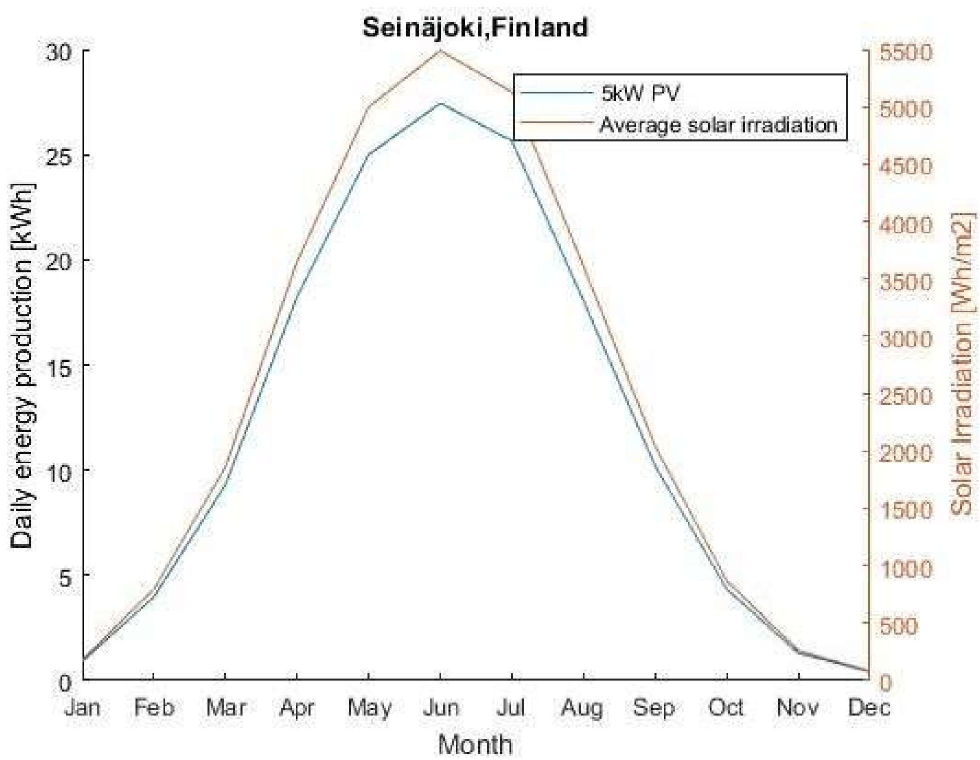

Figure 4.9. Average solar irradiation and energy produced for 5 kW PV installation.

4.2.4 Nunavut, Canada

In Nunavut, Canada the average daily irradiation for the year is almost 2040 Wh/m2 [30] which is small compared to the other regions even Seinajoki. Nunavut, Canada receives the lowest amount of irradiation in the cases discussed in this report and the period during which there is no or very little sun hours is even larger than in Seinajoki, Finlad discussed above. Figures 4.10 and 4.11 show the solar irradiation data and the energy that can be produced by PV installations of 1 kW and 5 kW for Nunavut, Canada.

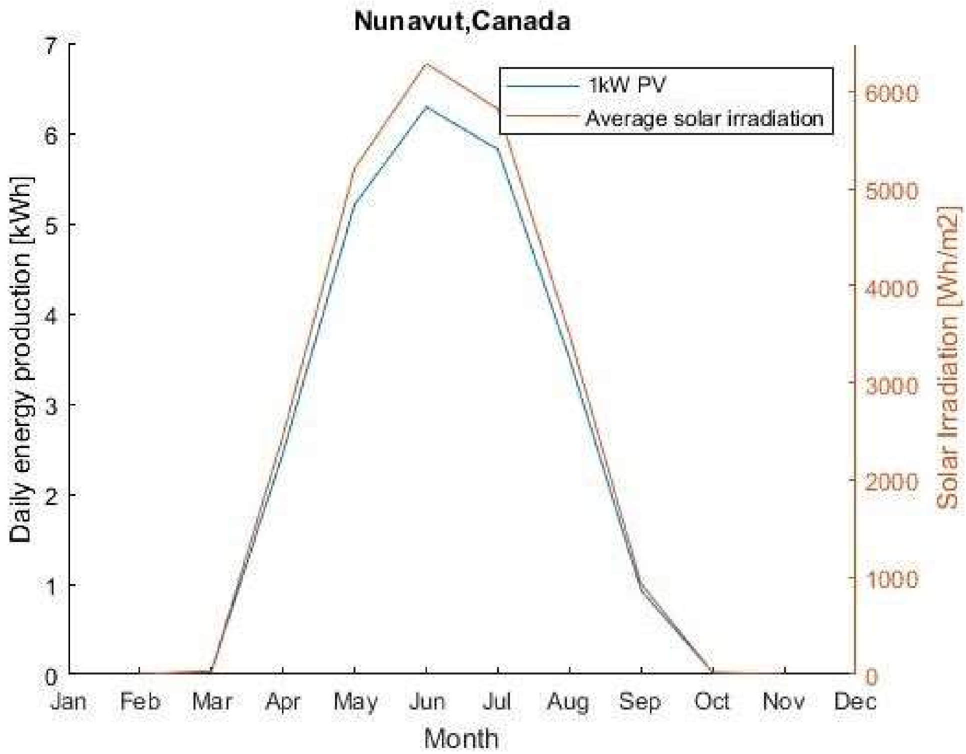

Figure 4.10. Average solar irradiation and energy produced for 1 kW PV installation.

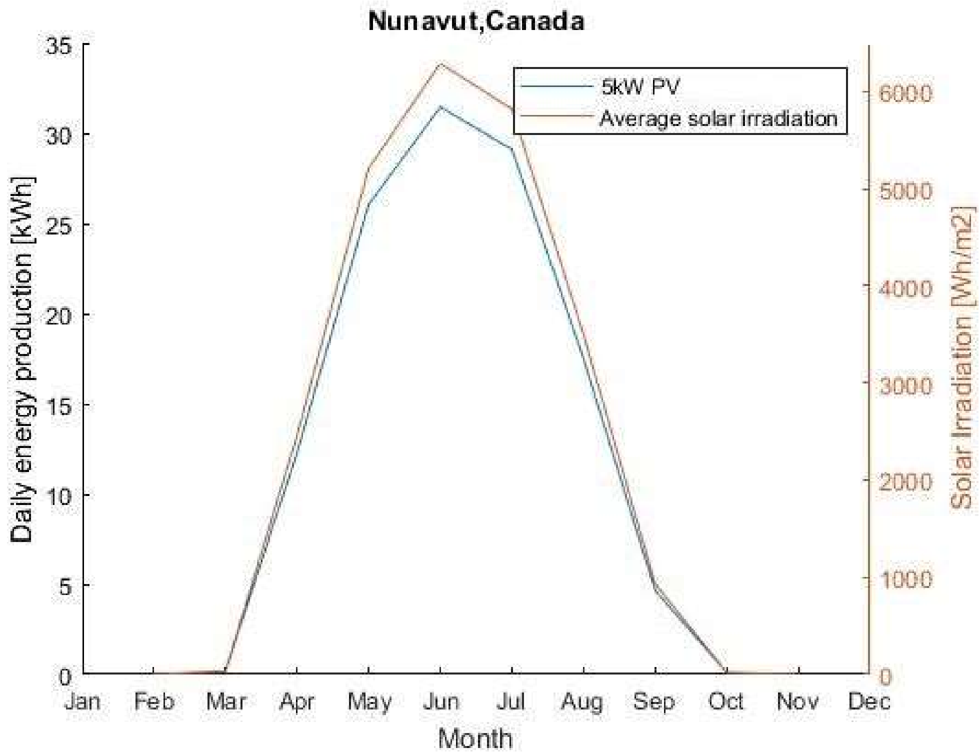

Figure 4.11. Average solar irradiation and energy produced for 5 kW PV installation.

4.3 Solar Power System

4.3.1 Solar Power System Setup

The elements of a solar power system are shown in figure 4.12. these elements are designed for easy installation and disassembly. Due to the recent significant development in solar technology, these components are designed to have high efficiency and low losses that will give more energy savings [31].

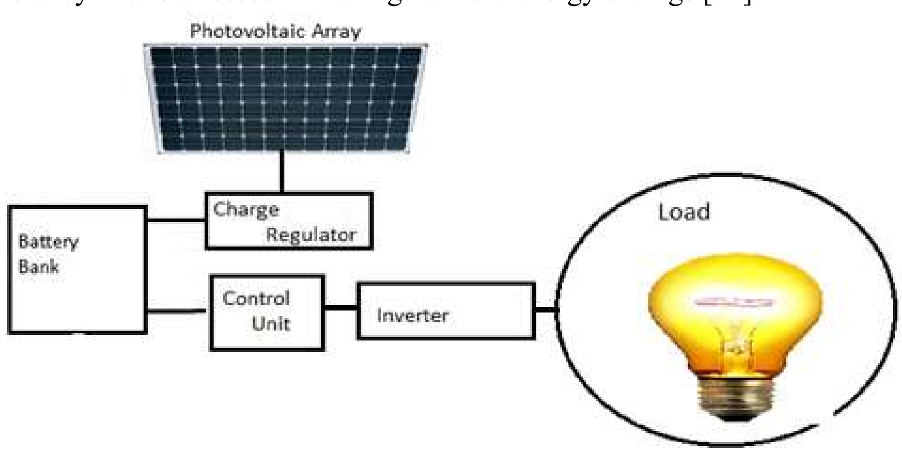

Figure 4.12. Solar power system setup.

- PV panels: converts the absorbed shortwave irradiance from the sun into direct current (DC) electricity.
- charge regulator: takes the unregulated DC energy from the PV panels and condition it to safely charge the storage devices or to provide power the load.
- Storage devices: store excess energy from the PV arrays to be used at night or when the power output of the PV panels is not sufficient. A charge control unit can protect the batteries by regulating the charging and discharging process and maintaining the battery lifecycle [31].
- Inverter: converts the regulated DC voltage from the charge regulator into 220 V alternating current (AC) voltage which is used to provide power the AC load.
- Control unit: manages and controls the power flow of the different elements in the solar power system to meet the demands of the load [31].

4.3.2 Photovoltaic mathematical model

4.3.2.1 Photovoltaic System

The output energy of the solar panels is calculated according to

$$Q_{pv} = Y_{pv} * F_{pv} * PSH, \tag{4.1}$$

where Y_{pv} is the capacity of the PV array, and PSH is the peak solar hour. F_{pv} is the PV derating factor, which reflects the impact of dust, wire losses, temperature, and other factors that can affect the output energy of the solar array [31,32].

4.3.2.2 Energy Storage

The maximum state of charge (SOCmax) of the battery bank is equal to the nominal capacity of the battery bank i.e. if the minimum state of charge (SOCmin) is 30%, it means the maximum energy that will be delivered from the battery bank is 70%. This value is called the depth of discharge (DOD) and is expressed as [31,32]

$$DOD = 1 - SOC_{min} \ . \tag{4.2}$$

The battery bank autonomy (A_{batt}) is an important factor that represents the potential number of days that the battery bank can feed the required energy load without contribution from the PV panels, and it is expressed as the ratio of the battery bank size to the load [31,32]

$$A_{batt} = \frac{N_{batt} * V_{nom} * Q_{nom} * \left(1 - \frac{SOC_{min}}{100}\right) * \left(\frac{24h}{d}\right)}{L_{prim} - avg}, \tag{4.3}$$

where N_{batt} is the number of batteries, V_{nom} and Q_{nom} are the voltage and capacity of a single battery, respectively, and $L_{prim-avg}$ is the average daily load. The battery lifecycle (R_{batt}) is another important issue that can reduce the total replacement cost during the project lifecycle. The throughput and the battery float life are the main factors that affect the battery lifecycle. The battery lifecycle can be calculated by [31,32]

$$R_{batt} = \min\left(\frac{N_{batt} * Q_{life}}{Q_{thr}}, R_{batt,f}\right), \tag{4.4}$$

where Q_{life} is the lifetime throughput of a single battery, Q_{thr} is the annual battery throughput, and $R_{batt,f}$ is the battery float life.

4.4 Wind energy

Wind energy is another form of renewable energy in which kinetic energy from the wind is used to rotate the turbines in order to produce electrical energy from them. Different regions exhibit different average wind speed characteristics which is dependent on the geographic location as well as the weather conditions of these areas. Figure 4.13 shows the wind map of the world for the average wind speeds in different regions.

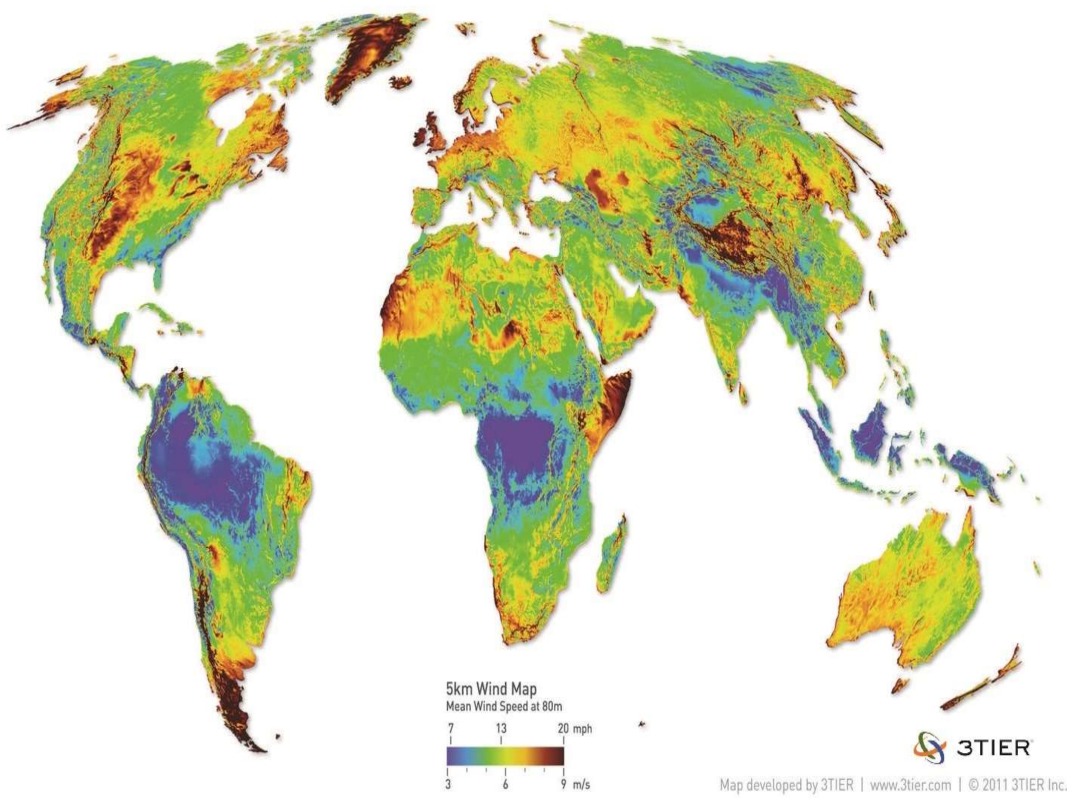

Figure 4.13. World wind map (© 2011 3TIER Inc) [33].

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Figure 4.13 distributes different regions based on their average wind speeds. The wind speeds fluctuate greatly daily during the entire year and so does the wind energy produced. Wind speeds also depend on the height of the wind turbines as at higher levels the wind speeds are greater compared to lower heights.

4.5 Wind power setup.

The elements of the wind power system are listed below, these elements are designed for easy installation and disassembly of small wind turbines for powering mobile base stations. Due to the significant development in wind power technology, these components are available with high efficiency and have low losses to provide energy saving. A wind power setup is shown in figure 4.14

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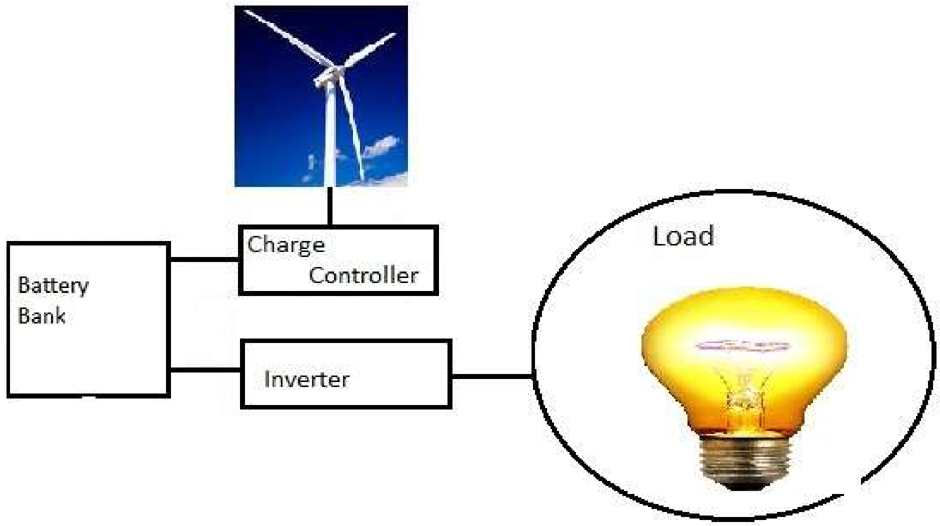
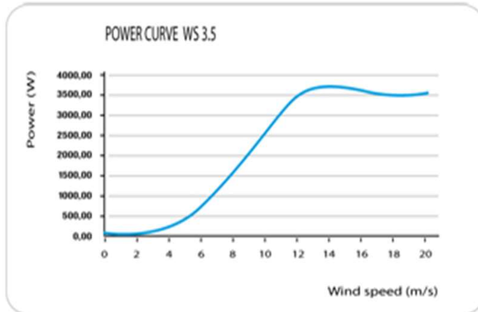


Figure 4.14. Wind power setup.

The components of the wind power generation system shown in the figure 4.13 are

- Wind Turbine: Converts the kinetic energy into electrical energy. Wind turbines consist of a tower and a wind energy generator. A tower supports the wind generator and elevates it to a height to get smooth and strong wind. The wind generator collects the energy in wind and converts it to electrical energy. The rotor blades of the wind turbine which powers generator to produce DC electrical voltage.
- Charge Controller: takes the unregulated energy from the generator and condition it to safely charge the batteries or to power the load.
- Inverter: converts the DC voltage of the DC bus-bar into 220 V alternating current (AC) voltage that is used to feed the AC load.
- Storage devices: store excess energy produced from the wind turbine to be used when the power output of the wind turbine is not sufficient.

Wind power generated from wind depends upon the wind speed and the capacity of the wind turbine used for wind power generation. Most turbines have a cut in speed of 3-3.5 m/s but recent developments in wind power generation wind turbines have been shown to produce power at speeds as low as 2 m/s. Figure 4.15 [33] shows the power vs windspeed curve of an example 3.5 kW wind turbine and table 4.1 shows some of the features of this turbine.



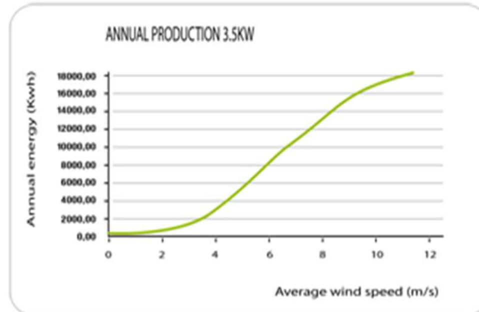


Figure 4.15. Power curve and annual energy production of a 3.5 kW wind Turbine.

Table 4.1. Features of example 3.5 kW wind Turbine [34].

Rotor diameter	4.05 m
Cut in speed	3 m/s
Rated speed	12 m/s
Weight	185 kg
Total length	3.2 m
Estimated Annual production	5500-11300 kWh at 5-7 m/s
Co2 savings	3610-7350 kg
Inverter	95% efficiency

4.6 Case studies for different regions.

4.6.1 Finland

The wind energy map of Finland based on average annual wind speeds is shown in figure 4.16. The wind map shows contrasting average wind speeds for different regions in Finland. The regions with wind speed less than 4 m/s are very close to the cut in speed of the wind turbines and the cost of wind energy production will not be ideal for wind turbine installations. But looking at the figure 4.16 it can be seen that in Finland for most of the areas wind speed lie in the range of 4-12 m/s which are very good speeds for wind power generation.

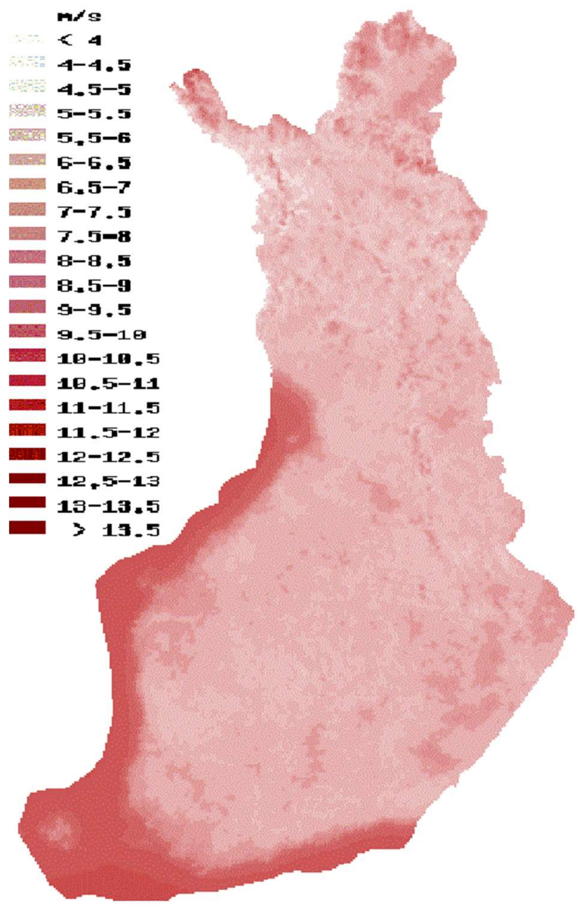


Figure 4.16. Wind Map of Finland [35].

From figure 4.16 the annual power production curve of a 3.5 kW turbine shows that in Finland regions where the average wind speeds are in the range of 5-12 m/s the annual power production lies in the range of 5500-18000 kWh. A load of 1 kWh requirement requires 24 kWh of energy per day or 8760 kWh per year. Although in Finland the temperature varies during the 12 months and during the winters the energy production of wind turbines can significantly drop due to cold weather and icing conditions which may also damage the wind turbines.

4.6.2 Nigeria.

Figure 4.17 shows the wind energy map of Nigeria. Nigeria is a warm country and there is no icing in the whole year. Therefore in Nigeria, the wind is a very viable source for producing electrical energy if the average wind speeds are sufficient.

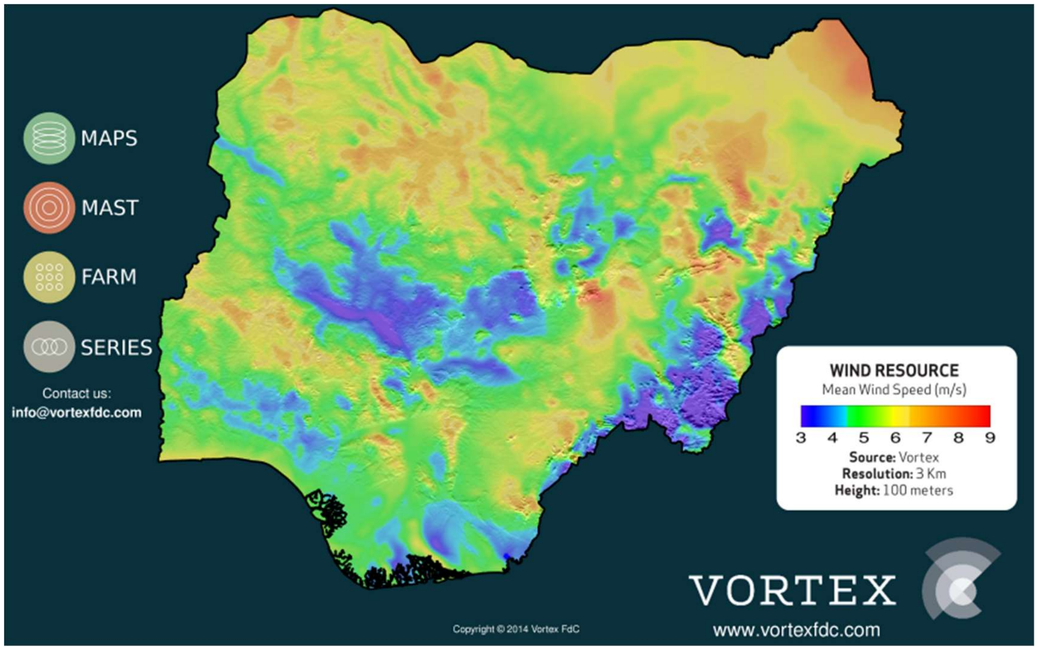


Figure 4.17. Wind map of Nigeria (© 2014 vortex FdC) [36].

From figure 4.17 it can be seen that for the most part of Nigeria the wind speeds lie in the range of 5-9 m/s. For this wind speed range, the 3.5 kW wind energy installation discussed in section 4.5 of this chapter can produce an annual average energy in the range of 5500-14000 kWh energy.

4.6.3 Australia

Australia is a sea locked country with moderate summers and moderate winters. The wind map of Australia is shown in figure 4.18. In most of Australia, there is no icing during the winters similar to Nigeria.

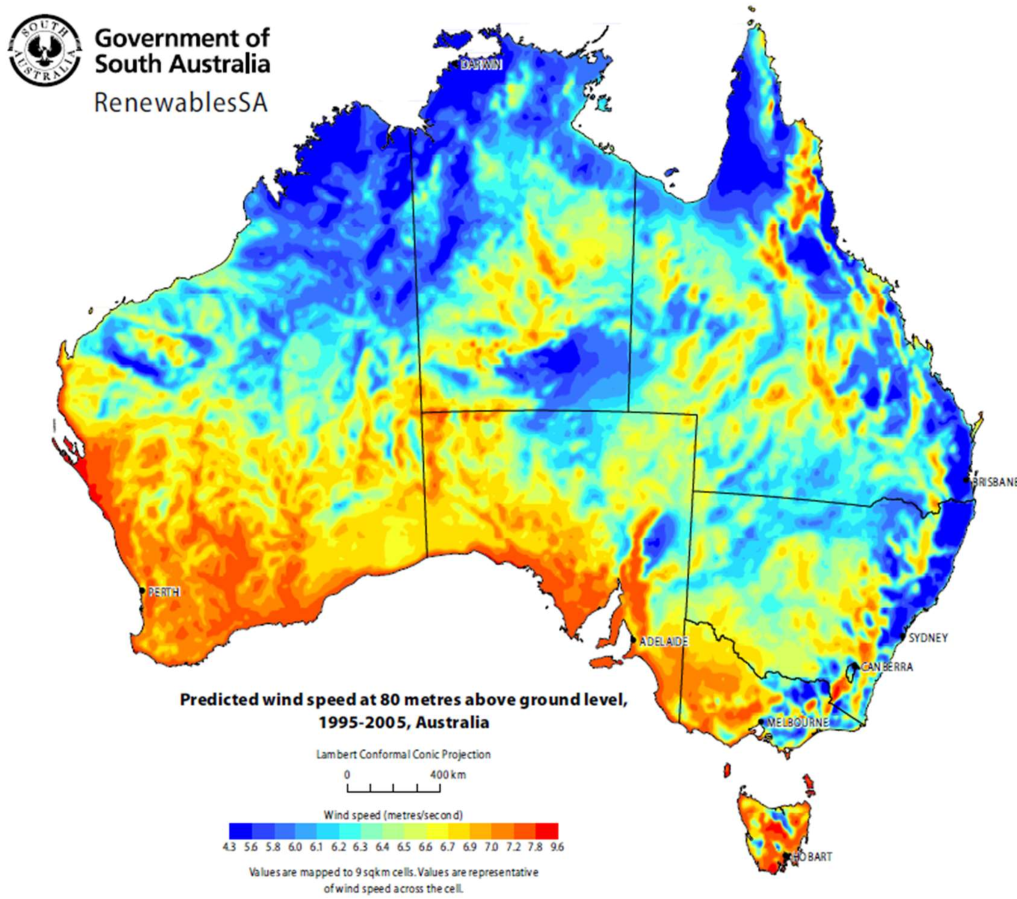


Figure 4.18. Australia’s wind map (© Winlab systems pty ltd) [37].

It can be seen from figure 4.18 that for Australia the minimum wind speeds lie in the range of 4.3-6 m/s and these wind speeds are not for the larger portion of the area. Instead for the larger portion of Australia, the wind speeds are greater than 6m/s. For the minimum wind speed range of 4.3-6 m/s, the 3.5kW turbine can produce 3500-8000 kWh of energy showing that wind energy holds promising future in Australia.

5 RENEWABLE ENERGY TO POWER BASE STATIONS

In this chapter renewable energy to power off grid base stations is discussed. The renewable energy setup to employ renewable resources such as solar and wind energy and also different configurations for the setups are discussed.

5.1 Configurations for renewable energy systems

There are four types of configurations that can be used to design renewable energy systems for powering mobile base stations; grid connected system with battery backup, without battery backup grid connected system, standalone system and hybrid standalone system [38].

5.1.1 Grid connected system with no battery backup

Grid connected system with no battery backup is a type of renewable energy system, in which the grid power is available, and the renewable energy is used alongside. In such systems, the power from renewable is used to provide energy to load and in case of insufficient power from renewable source, the grid power is utilized. Such system can be used for locations where there are power outages, i.e., bad grid sites. So in case of power outages the renewable energy can support the load. Fig 5.1 shows the setup for this system.

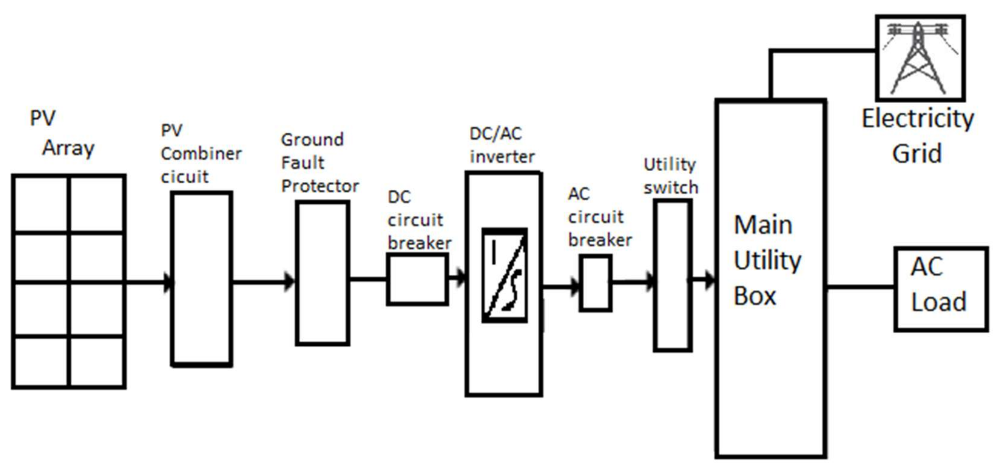


Figure 5.1. Grid connected system without battery backup.

Grid connected system without battery backup as discussed can be used for powering BSs in bad grid sites, but it is not an appropriate solution in such sites. This is because of the lack of battery backup, therefore in case of grid power failure and insufficient power supply from the renewable power source the system would fail to supply power. The BS would switch off in such situation which is not acceptable for the network operators.

5.1.2 Grid connected system with battery backup

Grid connected systems with battery backup use grid and renewable energy to power base station as well as to store power in the batteries. In case of grid power failure and insufficient renewable energy generation, the batteries can be used to power the base stations. This type of system can be used to power base stations in bad-grid sites. The setup for this system is shown in fig 5.2.

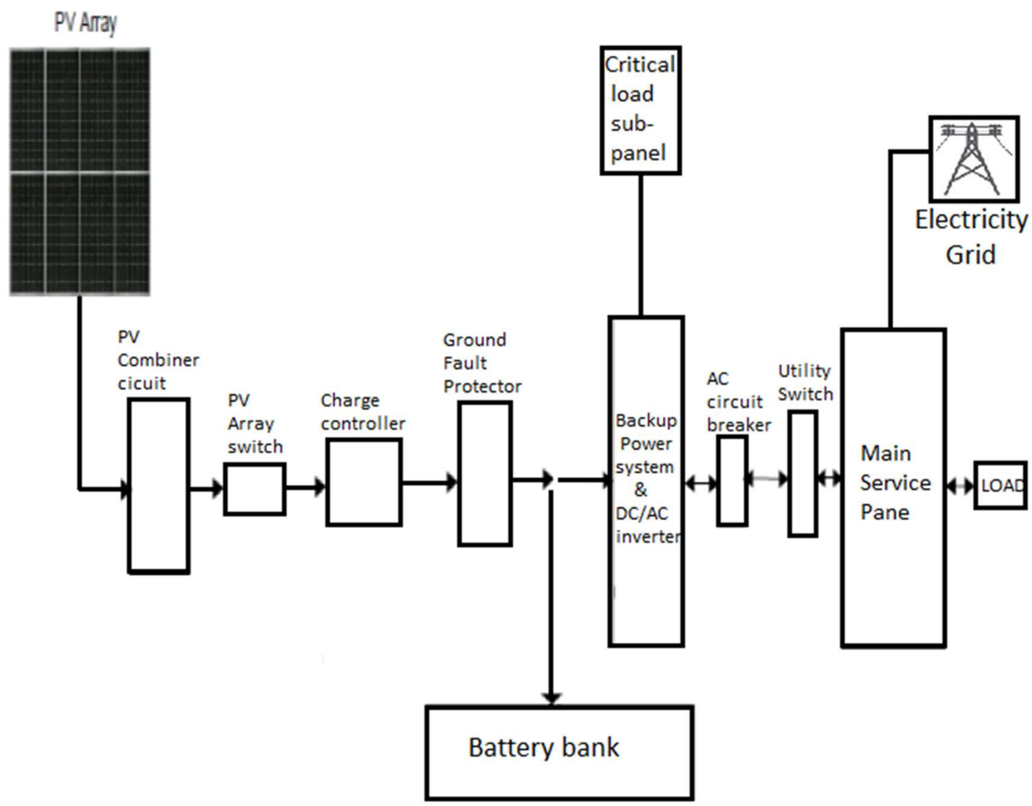


Figure 5.2. Grid connected system with battery backup.

Grid connected renewable energy system with battery backup are well suited for powering BSs in bad grid sites. In case of grid failure, the system can use renewable energy source and in case of both grid power outage and insufficient power supply from the renewable energy source, the battery backup can support the BSs.

5.1.3 Standalone renewable energy system

Standalone systems use a single source of renewable energy to provide power to the load. Standalone systems are always designed with battery backup because the renewable energy resources vary at different intervals of time. For example, solar irradiation varies almost every hour of the day and in most regions of the world, solar irradiation is negligible during the night. The setup for a standalone system is shown in fig 5.3.

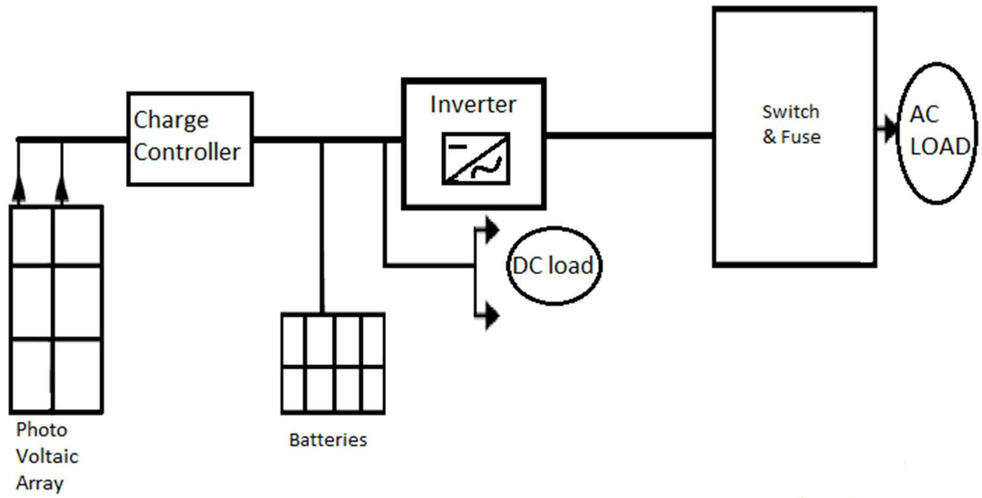


Figure 5.3. PV standalone system.

Standalone system can be used to power BSs in off grid sites. The renewable energy source to be used in such systems needs to be selected based on availability and climatic conditions of the location. Also, the battery backup system needs to be designed carefully depending on the climatic conditions as it would be critical for BS when the power from renewable energy is insufficient.

5.1.4 Hybrid standalone systems

Hybrid standalone systems are similar to stand alone systems, but these systems use more than one source of energy to provide power instead of relying on a single source. Hybrid standalone systems need less energy storage devices compared to the stand alone systems with a single renewable energy source. The hybrid standalone system can have a combination of renewable energy sources and it can have renewable and non-renewable energy sources such as diesel, natural gas etc. The setup for a hybrid standalone system with solar and wind energy sources is shown in figure 5.4.

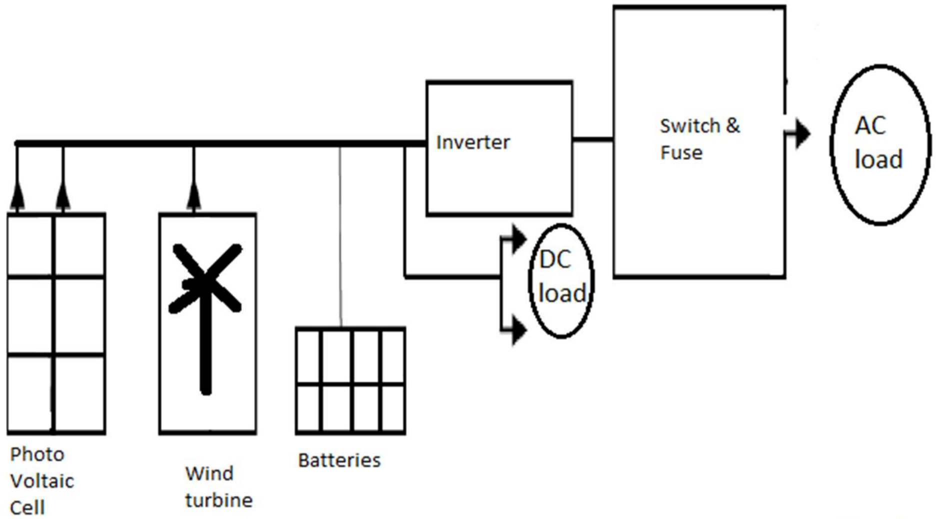


Figure 5.4. Hybrid standalone renewable energy system.

The above figure shows a hybrid system with only renewable energy as the source of power. The following setup shown in figure 5.5 shows a hybrid system which includes a diesel generator as a secondary source of power.

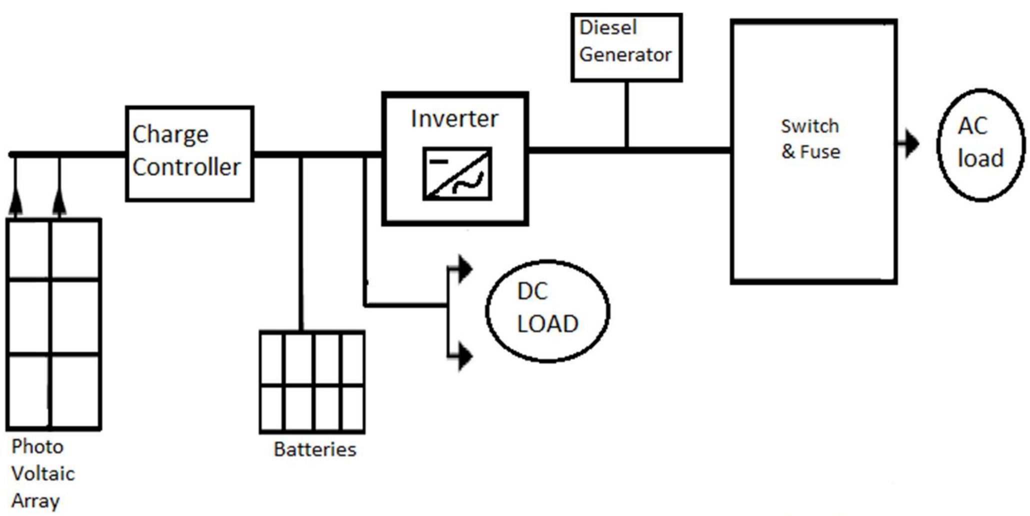


Figure 5.5. Solar and DG hybrid standalone system.

Hybrid standalone systems are very well suited for use in off grid BS sites due to multiple energy sources and battery backup system. So in case of insufficient supply from one source, the system can power the load from other energy source.

5.2 Solar powered cellular base station.

A setup for the solar powered cellular base station is shown in figure 5.6 [31]. A typical solar energy harvesting setup consists of PV panels, storage devices, and charge control unit and the load which in this case is a cellular base station. In this setup, the PV panels provide the required energy to the LTE macro base station. However, in an event where the power available from PV panels is not enough to provide the energy required to the LTE macro base station, the battery bank compensates for the shortage of energy. Furthermore, if the battery bank reaches its maximum depth of discharge (DOD) and fails to supply the LTE macro base station the required energy, a backup diesel generator can supply the required energy to the LTE macro base station. Hence, in this setup, the diesel generator is suggested as a backup power source to secure the power supply during maintenance or in case of a malfunction in the system or when the power from the PV system is not enough.

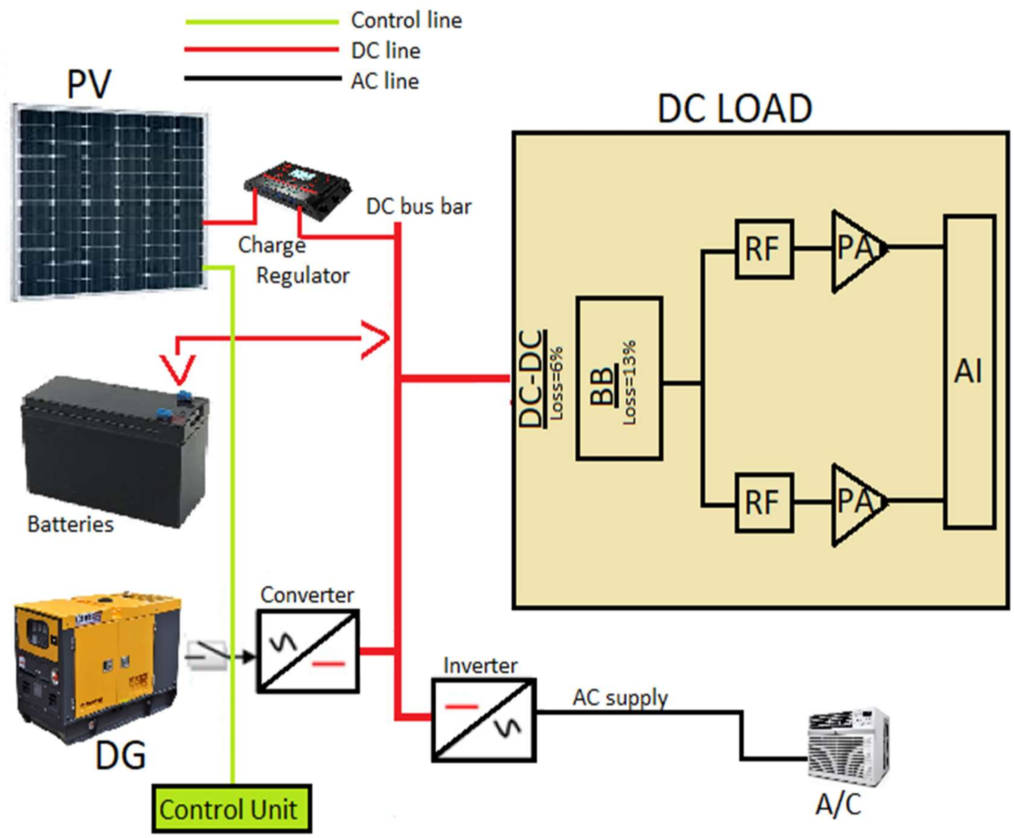


Figure 5.6. Setup for the solar powered cellular base station.

As shown in figure 5.6 the load, in this case, is the base station which consists of DC load and AC load. To discuss the power output requirement of the solar energy system we need to know first the power requirement of the base station. In table 5.1 a breakdown of power consumption of different equipment in a cellular base station is listed. For this study values listed in table 5.1 are for a 3-sector 4G LTE base station with a 2* 2 MIMO configuration obtained from [7].

Table 5.1. 4G LTE base station power consumption.

Item	Notation	Unit	Value
Power amplifier	P_{tx}	W	39.8
	η_{PA}	%	38.8

	P_{PA}^{DC}	W	102.6
RF equipment	P_{RF}^{DC}	W	10.9
Baseband	P_{BB}^{DC}	W	14.8
Losses	σ_{DC}	%	6
	σ_{cool}	%	10
No. of antennas			2
No. of sectors			3
Microwave link		W	80

The total input power per transmitter is $\frac{P_{PA}^{DC}+P_{RF}^{DC}+P_{BB}^{DC}}{(1-\sigma_{DC})} = 135.85$ W and there are two transmit antennas per each sector so the total input power is 135.85×3×2=815.1W. The power consumed by the cooling system is $P_{AC} = \left[\frac{P_{in}^{R}-500-P_{out}}{3}\right]^{+} = 85.43$ W. Another 80 W of power is used by the microwave link and 40 watts is used for the lighting. So this gives a total power consumption of 1020 W which can be approximated to 1 kW as the lights are on for certain period of time during each day.

To power, the 1 kW base station discussed above by solar energy alone means that the energy required by the base station for a day is approximately 24 kWh. Table 5.2 lists the average daily solar irradiation in a year for the locations discussed in chapter 4 and daily energy production in these locations for 0.5 kW and 1.5 kW solar installations in these regions.

Table 5.2. Average solar irradiation and energy production per day.

Location	Average daily irradiation (Wh/m^2)	Daily energy (kWh)	
		0.5 kW PV	1.5 kW PV
Seinajoki	82.1-5490	0.041-2.74	0.123-8.22
Girara	4380-7190	2.19-3.39	6.57-10.17
Nunavut	0-3330	0-1.66	0-4.98
Sokoto	5290-7190	2.64-3.58	7.92-10.29

PV panels are available with different output power levels which depends on the solar cell efficiency, for example, a PV panel with an efficiency of 0.2 will produce 200 W of power when the incident irradiation on it is 1 kW/m^2. The size of PV panels also differs slightly for different vendors. The size of PV panels can range from 1.3-1.7 m^2 with varying dimension but the most common size of the PV panels commercially available are 1.6 m^2 with a length of 65 inches and width 39 inches [39].

In this study PV panels with an efficiency of 0.189 and 1.6 m^2 size that are commonly available are considered. A 0.5 kW installation means that it consists of two PV panels and a 1.5 kW installation means it has 6 PV panels installed. To design a solar energy system to power a cellular base station in the regions listed in table 5.2 will require PV systems with capacities depending on their irradiation. In this study mathematical model for PV system described in chapter 4 is used.

From equation (4.1) the output energy of a PV installation is given as $Q_{pv} = Y_{pv} * F_{pv} * PSH$. So the required PV capacity of the system can be calculated as

$$Y_{pv} = \frac{Q_{pv}}{F_{pv} * PSH}, \tag{5.1}$$

where Q_{pv} is the required energy from the PV installation which in this case is the daily power consumption of the cellular base station that is approximately 24 kWh. F_{pv} is the derating factor that depends on the environmental conditions and its value may or may not vary many times over the course of a day and PSH is the peak solar hour which in this case will be the solar irradiation levels on horizontally placed PV panels. Horizontal placement of PV panels is used in this study in order to compute the required system capacity.

From Y_{pv} in equation (5.1) the required size of PV array for this system can be calculated as

$$Size\ of\ PV\ array = \frac{Y_{pv}}{\eta_{pv} * PSH}. \tag{5.2}$$

From the above equation (5.1) we can calculate the required capacity of the PV system that is enough to power a cellular base station. As solar irradiation levels differ for different regions below the required system capacity for the locations discussed in table 5.2 are calculated. In this study we are ignoring the environmental losses and wire losses i.e. PV derating factor is ‘1’.

Seinajoki:- In Seinajoki, Finland the average daily irradiation is 2420 Wh/m^2 but the solar irradiation varies aggressively during the months like in May and June the irradiation level can be as high as 5000 Wh/m^2 and in the months from December to February the irradiation levels are as low as almost close to zero. Table 5.3 list the PV system requirement for different months during a year.

Table 5.3. Monthly average irradiation and PV system requirements in Seinajoki.

Month	Average daily irradiation (Wh/m^2)	Required PV capacity (kW)	Size of PV array (m^2)
Jan	180	133.3	854.4
Feb	794	30.23	193.5
Mar	1860	12.9	83.2
Apr	3650	6.57	43.2
May	5000	4.8	32
Jun	5490	4.37	28.8
Jul	5130	4.68	30.4
Aug	3610	6.65	43.2
Sep	2040	11.76	76.8
Oct	868	27.65	177.6
Nov	259	92.66	593.6
Dec	82.1	292.32	1872

As seen from the table 5.3 the average solar irradiation differs during each month meaning the required system capacity is different for each month. During the months October to February when the irradiation is less than 1000 Wh/m^2/day the required system capacity is very high. To design a PV system for these months would have a very high capital investment (capex) and the cost of power generation would be very high. In the months February to September the highest PV capacity requirement is 12.9 kW. A 15 kW standalone PV system would be suitable to power base station in these months with irradiation greater than 1 kWh/m^2/day but when the irradiation is less than that as in the months October to February it cannot provide the required power. Figure 5.7 shows the output energy of 2, 4 and 7.5 kW PV installation and the daily energy requirement of a BS.

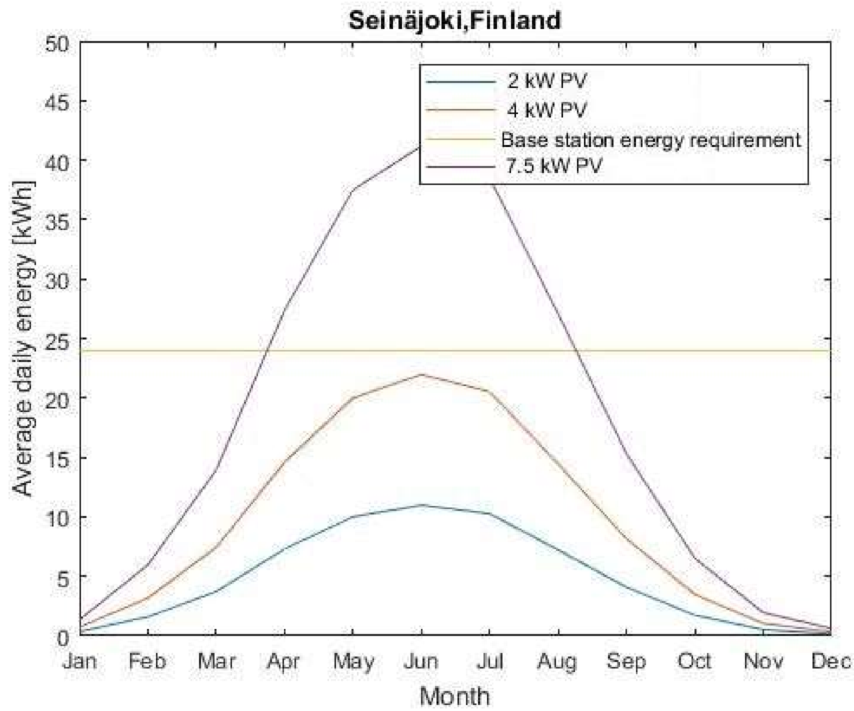


Figure 5.7. Average daily energy production for 2, 4 and 7.5 kW PV installations.

As seen from the figure 5.7, the 2 and 4 kW systems cannot meet the power requirement of the BS but the 7.5 kW PV systems can power the BS only during the months April to August. For the period of September to March the energy produced from the 7.5 kW systems does not meet the BS requirement. Looking at table 5.3 and the figure 5.7 it can be deduced that a standalone solar energy system is not a feasible option in this region and there must be a backup power source to power the BS during the months when solar energy is not enough.

Girara: - The average solar irradiation in Girara, Indonesia is 5950 Wh/m^2/day. The lowest average irradiation per day occurs in the month of July during which the average irradiation per day is 4380 Wh/m^2 which is almost double compared to the average irradiation level in Seinajoki discussed above.

Table 5.4. Monthly average irradiation and PV system requirements in Girara.

Month	Average daily irradiation (Wh/m^2)	Required PV capacity (kW)	Size of PV array (m^2)
Jan	6260	3.83	24.5
Feb	6790	3.53	22.6
Mar	7190	3.34	21.3

Apr	6330	3.80	24.26
May	6060	3.96	25.34
Jun	5250	4.57	29.25
Jul	4380	5.47	35.06
Aug	4770	5.04	32.20
Sep	5620	4.27	27.33
Oct	6200	3.87	24.77
Nov	6380	3.76	24.07
Dec	6240	3.84	24.62

In this region, the solar irradiation levels are enough to power the BS as calculated in table 5.4 the maximum PV capacity required is 5.47 kW during the month of July during which the average irradiation is the lowest. Compared to Seinajoki the irradiation levels in this region are very good and also the irradiation levels do not fall as low as Seinajoki during all the months. From the table 5.4, it can be seen that by careful planning of the energy storage options according to the geographical conditions in this region solar energy system is a viable option to power BSs without the need for any other energy source.

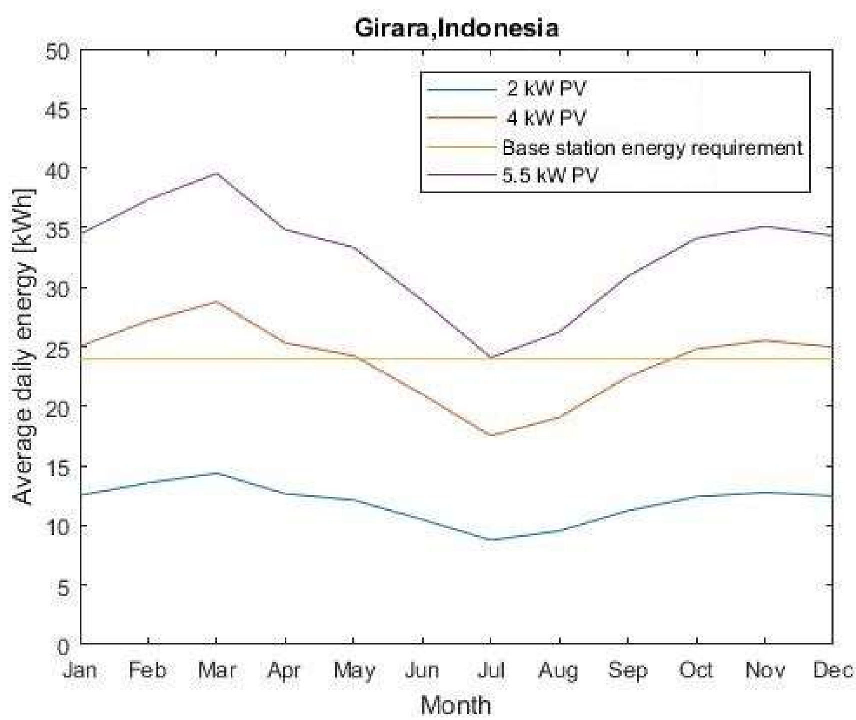


Figure 5.8. Average energy from 2, 4 and 5.5 kW PV installations.

Figure 5.8 shows the output power for 2, 4 and 5.5 kW PV installations. The 2 kW PV system would not be enough to power a BS. The 4 kW system can partially fulfil the BS requirement during the months January to May and October to December. To design a standalone solar energy system for the BS in this region would require a PV installation of 5.5 kW with battery backup for situations when the energy from PV is not enough. This concludes that in this region and other regions with similar irradiation a standalone solar energy system to power BS is a suitable option. Also in such regions off grid BS sites where DGs are already in use using a solar energy system along with DG would not only decrease the operating cost (opex) for network operators it would also reduce the GHG emissions from such BS sites.

Sokoto: - This region similar to Girara is a very good location for harnessing solar energy as the lowest average irradiation is 5290 Wh/m^2/day during the month of august and maximum during the month of 7160 Wh/m^2/day.

Table 5.5. Monthly average irradiation and PV system requirements in Sokoto.

Month	Average daily irradiation (Wh/m^2)	Required PV capacity (kW)	Size of PV array (m^2)
Jan	5660	4.25	27.13
Feb	6230	3.85	24.66
Mar	7160	3.35	21.45
Apr	6650	3.60	23.1
May	6460	3.71	23.78
Jun	6270	3.82	24.5
Jul	5720	4.19	26.85
Aug	5290	4.53	29.1
Sep	5910	4.06	25.99
Oct	6120	3.92	25.1
Nov	5760	4.17	26.67
Dec	5490	4.37	27.98

The required PV capacity per month in Sokoto shown in table 5.5 ranges from 3.35 kW to 4.5 kW. So. a 4.5 kW PV standalone system would be enough to power a cellular base station in this region as illustrated in figure 5.9 below along with average energy output of a 3 kW PV system.

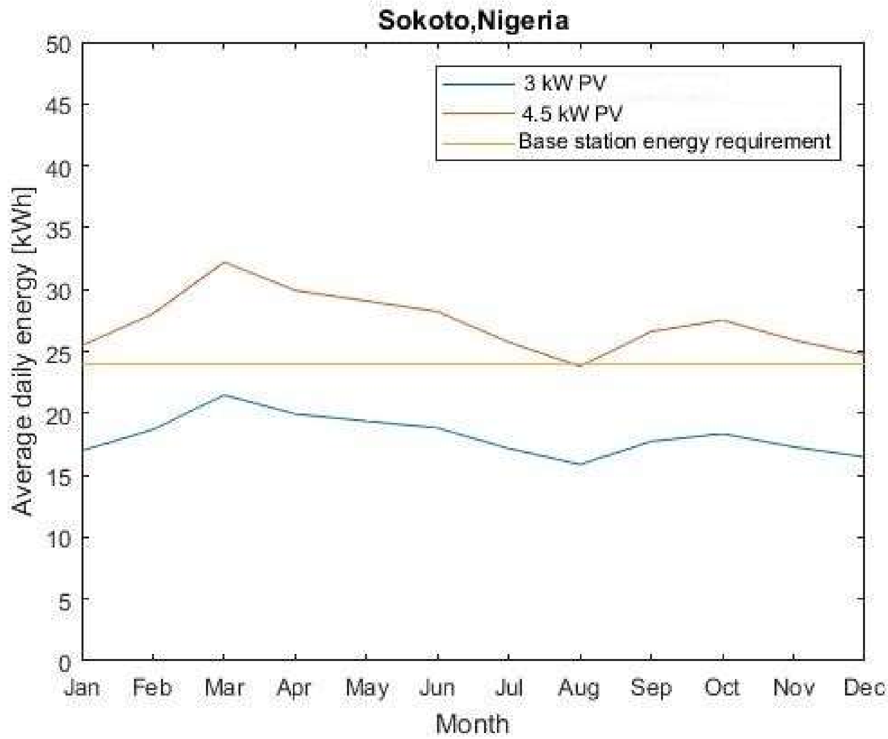


Figure 5.9. Average energy production from 3 and 4.5 kW PV systems in Sokoto.

The power produced by 3 and 4.5kW shown in figure 5.9 and the energy requirement of base station shows that like the Girara region discussed above the solar energy is a very viable power source for off grid cellular BSs. Thus it emphasizes the use of standalone solar energy systems in such areas with high solar irradiation.

Nunavut:- The solar irradiation in Nunavut, Canada listed in table 5.2 range from as low as 0 to 6290 Wh/m^2/day. The average solar irradiation in this region is even lower than Seinajoki that was discussed above. The average irradiation per day for a year is approximately 2040 Wh/m^2/day whereas monthly average irradiation along with the required PV capacity are shown in table 5.6.

Table 5.6. Monthly average irradiation and PV system requirements in Nunavut.

Month	Average daily irradiation (Wh/m^2)	Required PV capacity (kW)	Size of PV array (m^2)
Jan	0	---	-----
Feb	0	---	-----
Mar	0.034	706	4518.4
Apr	2.46	9.76	62.4
May	5.21	4.61	30.4
Jun	6.29	3.82	25.6
Jul	5.82	4.12	26.37
Aug	3.50	6.86	44.8
Sep	0.93	25.81	166.4
Oct	0.02	1200	7680

Nov	0	---	-----
Dec	0	---	-----

Looking at table 5.6 shows that only the months April to August have solar irradiation during which it is possible to harness the solar energy. Therefore, a standalone solar energy system would not be a possible solution to power cellular base stations in this region. This can also be seen from figure 5.10 that shows the base station energy requirement and the average energy produced by the 4 and 7.5 kW PV installations.

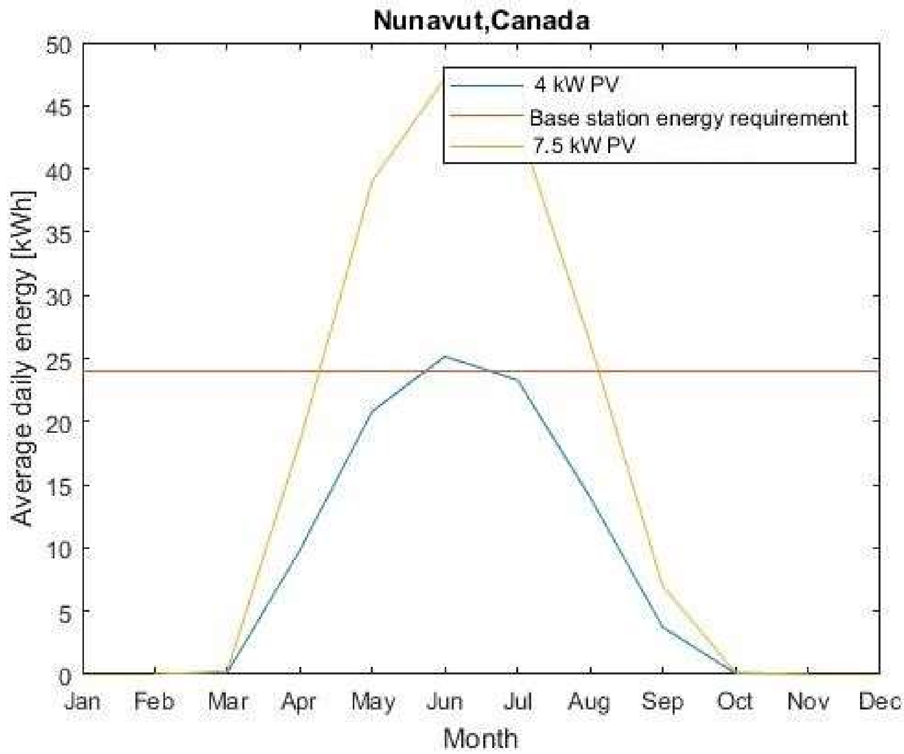


Figure 5.10. BS energy requirement and energy produced by 4 and 7.5 kW PV.

Figure 5.10 again emphasizes that stand alone solar energy system is not well suited for Nunavut Canada and similar regions as the energy produced from both 4 and 7.5 kW is not enough for the cellular BS for most of the year. This emphasizes the need for another power source which can be used alongside solar energy or which alone is enough to power the base station in such regions.

5.3 Wind powered cellular base stations

The setup for powering base station using wind energy is very similar to the solar powered base station system discussed above in section 5.2 except the PV panels are replaced with a wind turbine for power generation using the wind kinetic energy. The setup for wind powered cellular base station is shown in figure 5.11.

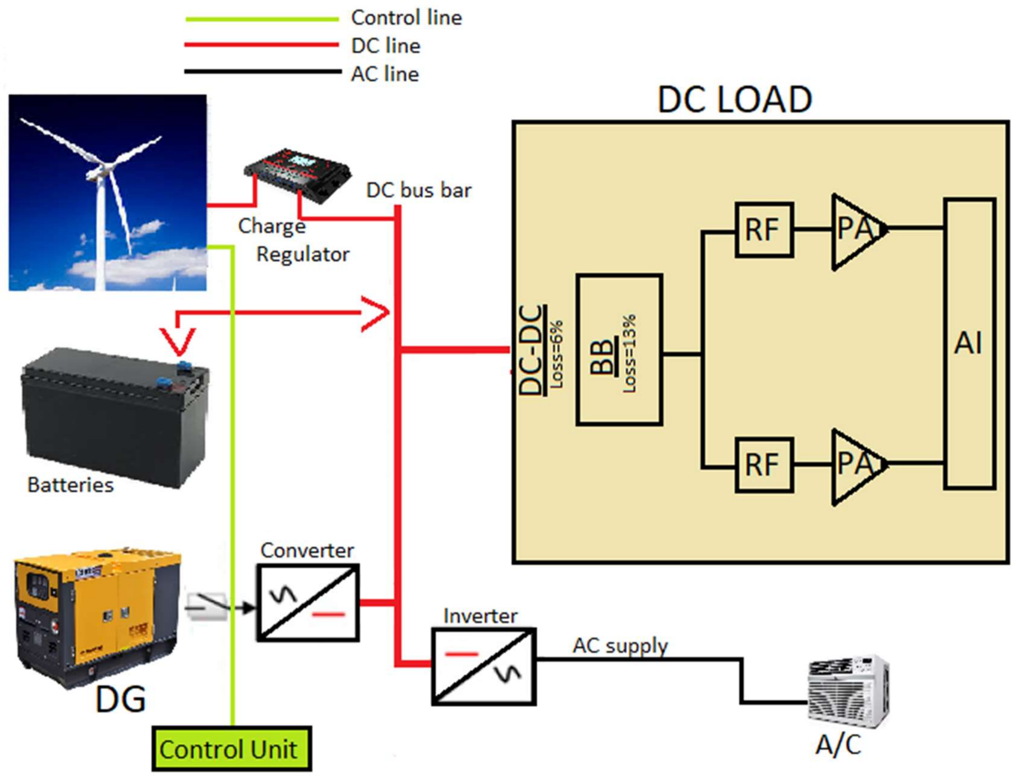


Figure 5.11. Wind powered cellular base station setup.

Small wind turbines are available now which can be used to power cellular base stations [33,38]. The power production from these turbines depends on the wind speeds and capacity of the wind turbine. Characteristics of a 3.5 kW turbine were discussed in section 4.4. Table 5.7 list the average yearly energy and power production for different wind speeds for this 3.5 kW wind turbine.

Table 5.7. Average power production for 3.5 kW wind turbine

Wind speeds (m/s)	Power production (kW)	Annual energy production (kWh)
<3	<200	<1700
4-5	250-500	3500-5500
5-6	500-750	5500-8000
6-7	750-1200	8000-10500
7-8	1200-1500	10500-13000
8-9	1500-2000	13000-15000
9-10	2000-2500	15000-16000
10-12	2500-3500	16000-16500
>12	Up to 3700	Up to 18000

The average daily energy requirement of a base station as calculated earlier is 24 kWh. So, the annual energy required by the base station will be 365×24=8760 kWh. From table 5.7 it can be seen that regions, where the average wind speeds are in the range of 6-7 m/s this turbine, can be used to power a cellular base station by wind energy alone. Also, other small wind turbines of bigger capacity are also available for that produces more energy at lower wind speeds. For example, a 7.5 kW turbine manufactured by the same company of 3.5 kW wind turbine that is mentioned above. The 7.5 kW turbine can produce 5000-10,000 kWh energy per annum for the average wind speeds in the range of 3.8-5 m/s. The windspeed vs energy curve for the 3.5 and 7.5 kW wind generator for varying wind speeds is shown in figure 5.12 [40].

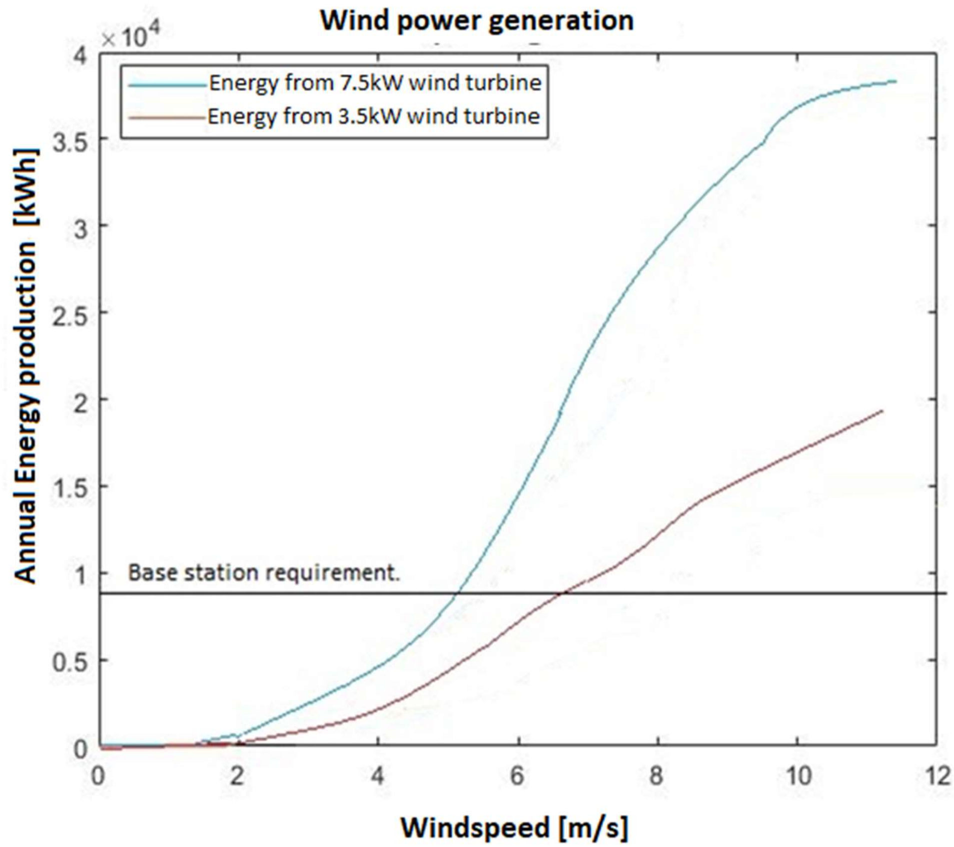


Figure 5.12. The wind-power curve of 3.5 and 7.5 kW wind turbine.

As seen from figure 5.12 wind energy in regions with wind speeds averaging 4-8 m/s could be used as a viable source of renewable energy to power cellular base stations. But wind speeds are not constant for every region and wind speeds change at many instants during the day. Therefore, alternate solutions are required to power base station rather than using the wind energy alone like hybrid systems can be used or generator backup is available. Another way is to design storage devices in a way such that they can provide backup when the windspeeds are not high enough and when windspeeds are high they quickly store up the energy to be used later.

5.4 Hybrid energy system.

In section 5.2 and 5.3 standalone systems using solar and wind energy sources are discussed to power the base stations. In case of solar energy there were regions discussed where solar energy is not a constant power source and during the year there are periods when the solar irradiation is almost zero. Similarly, in case of wind energy even if the average wind speeds are above 4 or 5 m/s there are durations during which the wind speeds are lower than 3 m/s which is the cut in wind speed after which the turbine starts producing power. These problems can be overcome by using hybrid energy sources, for example, using both solar and wind energy or solar energy and diesel generator to power the base stations. In that case when one resource is absent for long periods of durations the other energy resource can compensate. And in the absence of all the renewable energy resources, the storage devices can provide backup. Also in this type of hybrid system, the need for a backup generator in case of a malfunction is greatly reduced. With the suitable planning of storage devices, the need for DG to power base station when power from both the energy sources is insufficient can be avoided.

Studies have shown that hybrid systems that use diesel and renewable energy resources are not only more reliable than standalone renewable energy systems but they also reduce the opex of the base station sites. Although these hybrid systems may have more capex compared to standalone systems, on the long run, they are a cheaper source of power compared to the conventional DG standalone systems and also, they significantly reduce the CO2 emissions [41,42].

5.5 Energy storage devices

There are a number of energy storage options available these days and research is ongoing for making storage devices more compact with greater storage capacity and longer lifetime. A number of storage devices that can be used to store excess energy to be used later are listed in table 5.8.

Table 5.8. Storage options for small renewable energy systems [43].

Type	Cycles	Wh/kg	Density (kWh/m^3)	Efficiency (%)
Li-ion	500-1000	100-265	500	95
NiMH	500	100	140-300	65
Lead acid	500	33-42	60-110	50-95
NiFe	5000	19-25	125	65-80

Table 5.8 discusses a few energy storage options available with Li-ion and lead acid batteries being the most commonly used. Battery cycles are used to tell the life expectancy of a battery as it tells how many time a battery can undergo the process of charging and discharging before failure or losing its capacity. The battery density listed in the table tells how much power it can store per unit volume. And the battery efficiency is the ratio of energy obtained from discharging to energy used in charging.

Based on required energy for a base station that was calculated to be 24 kWh/day the volume of batteries required to provide this required energy will be 0.25 m^3 in case of lead acid or 0.05 m^3 in case of Li-ion batteries is required. Table 5.9 shows the volume of different storage devices discussed above required to power base stations for different time intervals.

Table 5.9. Volume of different storage devices to power base station

No. of days	Li-ion (m^3)	NiMH (m^3)	Lead acid (m^3)	NiFe (m^3)
1	0.05	0.12	0.25	0.192
3	0.15	0.36	0.75	0.576
9	0.45	1.08	2.25	1.728
30	1.5	3.6	7.5	5.76

5.6 Motivating factors for renewable energy base stations.

In this section are a few advantages and motivating factors for adopting wind and solar energy to power cellular base stations for network operators in order to ease deployment in remote and rural areas.

Cost savings: - Although the capex for solar or wind powered base stations is higher compared to the DG the opex is much smaller compared to the DG. For DGs, the opex comes from the use of fuel and for renewable energy base stations, it comes from the cost of replacing the batteries. Wind and solar energy setups have a greater lifetime than DGs and DGs needs to be changed after a shorter period of time compared to wind and solar energy setups that can last up to 25 years.

Simpler maintenance: - In comparison to DGs where there is need to refill fuel and maintenance is required periodically renewable energy base stations have a very low maintenance cost.

Disaster resistance: - Traditional grid connected systems fail when there is grid failure for extended periods of time. For example, in 2011 more than 6700 base stations experienced a power outage due to tsunami [42].

Government regulations and subsidies: - Many countries currently promote and offer subsidies for use of renewable energy.

Greener energy: - Renewable energy use implies that there are no harmful emissions during operation compared to DGs.

5.7 Challenges for adopting renewable energy.

In this section are listed some of the challenges accompanied with the use of renewable energy for powering cellular base stations. These challenges if addressed properly can greatly motivate the operators to expand the cellular networks into remote locations and will help in reliable and greener cellular communications.

Economic challenges: - Though in the long run renewable energy is more economical then DGs, operators choose to use DGs for powering base stations because of the high capex required for installing renewable energy systems. Also, the power required by a base station is high and in order to design a system that meets the requirement increases the capex of the system.

Geographical limitations: - As discussed earlier in section 5.2 there are regions that have poor solar irradiation and in case of wind energy the wind speeds vary many times during a day. In regions where the weather is bad for longer durations the need for larger battery banks increases significantly.

Resource positioning and deployment: - The successful deployment of renewable energy base station will require careful planning to determine the optimum number of PV panels and batteries required for the system. Over dimensioning the system can lead to very high capex and under dimensioning can lead to frequent power outages.

6 DISCUSSION

Several studies have been done about reducing the power consumption of base stations and the new 5G BSs is going to reduce the power consumption of BSs by almost 65% compared to the power consumption of its predecessor 4G LTE BSs. A study conducted by Alcatel lucent in 2010 shows the evolution of BSs energy efficiency overtime and it predicts the reduction of BS power consumption in the coming years shown in figure 6.1 [44].

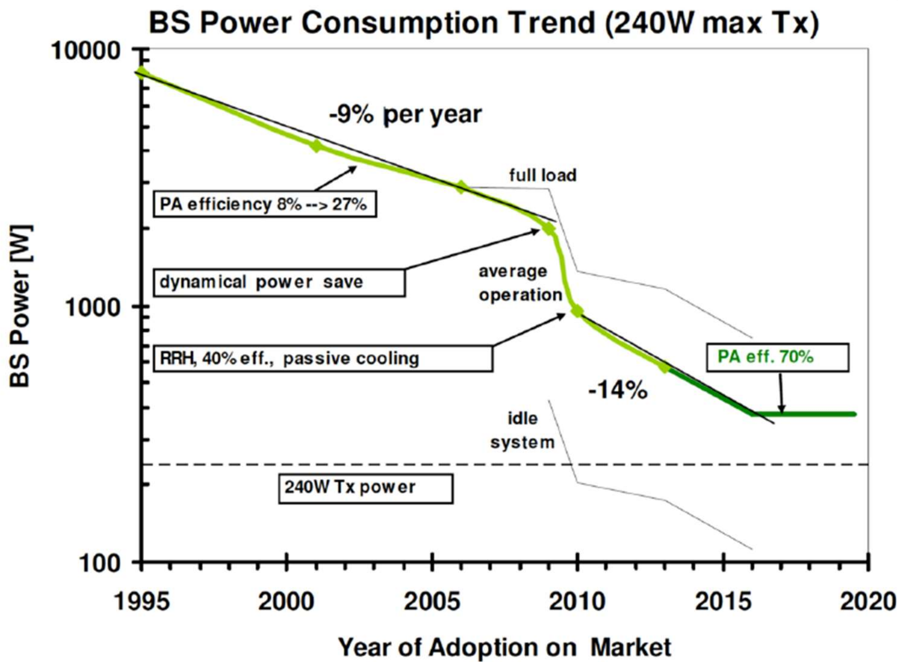


Figure 6.1. Base station power consumption over the years.

Figure 6.1 suggests that in the upcoming years the BS station power consumption can be reduced to 300 watts which is a target that seems achievable in the upcoming 5G access network. Also, the prices of wind and solar energy system for deployments on small scale has been said decreasing. Figures 6.2 [45] and 6.3 [23] shows the trend of prices of PV panels and batteries over the last years. BSs with power consumption as low as 300 W and with reduced prices of renewable energy the deployment of BSs in remote and rural areas will be highly facilitated economically as revenue per user is the biggest concern for operators in remote areas. Also, it would highly encourage the network operators to adopt renewable power sources. Discussed in section 5.2 were the PV capacity requirements for 1 kW system. A 300 W BS would reduce the required PV capacity to 1.5 and 2 kW in case of Sokoto and Girara respectively. In case of high latitude regions like Seinajoki and Nunavut discussed earlier powering a 300 W BS still might not be possible with standalone solar energy system because of negligible irradiation levels that last for months. But during the months when the solar irradiation is enough a 2.5 kW PV system would be enough to power such a BS. Also discussed in section 5.3 was the use of wind energy to power BSs. The annual energy requirement of a 300 W BS would be $\frac{300}{1000} \times 24 \times 365 = 2628$ kWh which can be harnessed using the 3.5 and 7.5 kW wind turbines at average windspeeds of 3.5 and 5 m/s respectively.

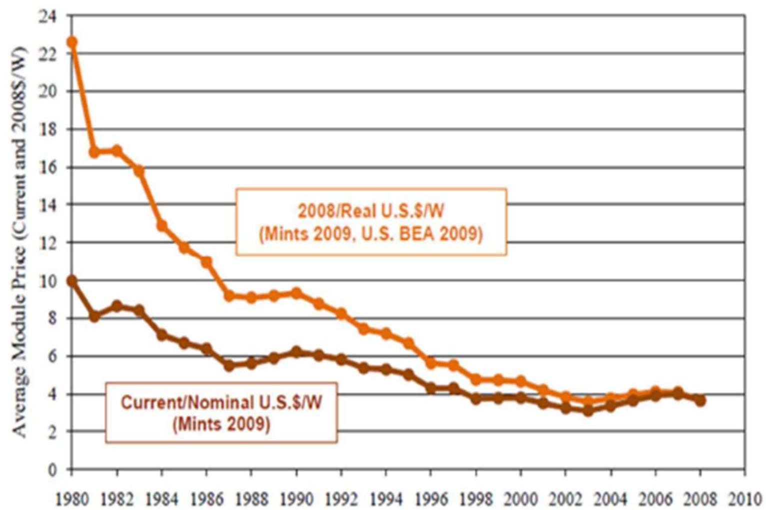
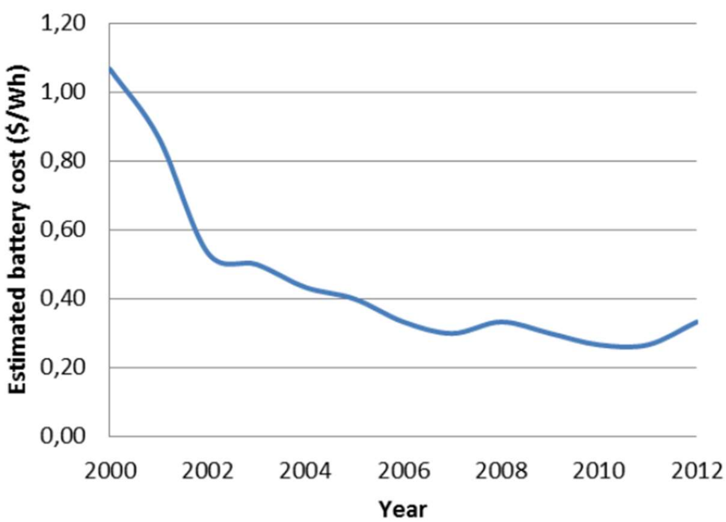


Figure 6.2. Prices of PV panels over the past years.

Figure 6.2 shows the trend of PV panels prices in the past years. It can be seen clearly that with each passing year the prices are decreasing and if this continues in the future the solar energy installations will grow at a higher rate in the coming future.



`Figure 6.3. Li-Ion battery prices variation within the last decade.

From figure 6.3 deducing that if the reduction in the batteries price keeps on storage options would become more feasible to design standalone systems. Increased storage capacity would facilitate standalone systems with only wind or solar energy, where DG used only to provide backup power when power from the renewable energy sources is not enough.

Future research challenges

We have discussed the approaches to reduce base station energy consumption and approaches to power base stations in the absence of grid energy that leads to further research questions. Few of those are

- How much can the cell size be increased by massive MIMO UE-beamforming while still maintaining the data rate defined by 5G?
- How the beamforming and ultra-lean system design can enable economically sustainable coverage in remote areas?
- How much can energy 5G save through energy-efficient deployments?
- Designing the storage devices when solar power and wind power both are used and there is no backup DG.
- How to design a cost-efficient wind generator that can operate in harsh winter conditions?

7 SUMMARY

Communication services to all the people is considered an important component of social justice and it cannot be compromised due to economic reasons. Growing attention from governments and support from academia has motivated the network operators to better drive cellular networks in the remote and rural areas. The deployment of new BSs in remote sites is inhibited by factors such as the high energy requirement of cellular BSs, low number of subscribers, unavailability of reliable grid power and cheap reliable alternate power sources in these areas.

In a cellular network, the BSs are the major component that consumes up to 80% of total power consumption of the cellular network. Therefore, energy efficiency has been an interest of research in the recent years. The power consumption of base station is better understood by learning the structure and power breakdown of each component in the base station. This would help develop a better idea of the base station and give an insight to how and on where we can achieve better power efficiency in the base station.

Various research schemes have been proposed which focuses on lowering the power consumption of the base stations that include optimizing the efficiency of base station components such as power amplifier, reducing the losses such as feeder losses. Introducing sleep modes so that base station or certain functionalities of the base station stop when there is no or less traffic in the cell has also been discussed. Deployment of heterogeneous networks and optimizing the radio transmission process to achieve energy efficiency with techniques such as MIMO, cooperative relaying, cognitive radio had been proposed. The upcoming 5G technology promises very high energy efficiency of the BS by employing beamforming through massive MIMO and ultra-lean system design to enable deep sleep modes.

In remote areas, the grid power is not always available thus emphasizing the need for alternate energy sources to power BSs. The most feasible energy resources available in remote areas include the solar energy and wind energy. Solar and wind energy production varies for different locations depending on the geographic and climatic conditions. Solar energy systems consist of PV panels, inverters, batteries and charge regulators. Wind energy systems comprise of wind turbines, inverters, and batteries.

We analysed different locations for deployment of BSs using the solar and wind energy. It was shown that there are locations where solar energy is a very feasible option for powering BSs because of the high solar irradiation in these regions and we also discussed regions where the solar energy alone is not enough for powering the BSs. We also analysed the solar energy setup for BS at locations where the energy production from PV installations meets the BS requirement during a certain part of the year whereas rest of the year it does not meet the minimum power requirement. In case of wind energy at every region the wind speeds vary during different time intervals and designing a standalone wind energy system would be difficult without backup power. But wind energy system along with solar energy systems can be used to power BSs in situations where there is another source of renewable or non-renewable energy source available.

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